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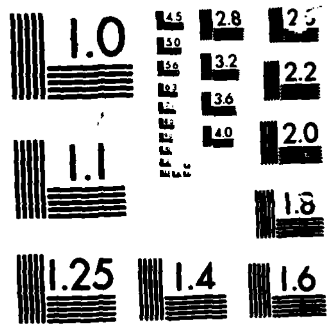

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ABSTRACT

Anomalous United States Weather Patterns Accompanying
Stratospheric Sudden Warming. (May 1985)
Donald Albert Douglas, B.S., University of Utah
Chairman of Advisory Committee: Dr. James P. McGuirk

Key signatures of tropospheric circulation are investigated for months during which major Stratospheric Sudden Warming (SSW) occurred in the period 1955 to 1980. For the contiguous United States, monthly values of cyclone frequency, storm paths, precipitation and surface temperature are determined for 17 January and February months and compared against the years in which no SSW events occurred. Consistent with studies of energetics which show that the troposphere loses energy to the stratosphere during SSW, cyclone frequency is approximately 22% less during SSW. Also, consistent with a modification of planetary-scale waves during SSW, mean storm tracks are altered. Most notably, the Colorado Low disappears during SSW. Precipitation totals reflect the changes in cyclone behavior. The Ohio River Valley is the most anomalously dry region of an abnormally dry United States during SSW. During February, the southwestern states exhibit anomalously high precipitation totals. Surface temperatures are significantly below normal, especially east of the Rocky Mountains. During January, every state shows below normal temperatures except Nevada. The February

SSW mean temperatures are warmer than normal from the Rocky Mountains westward and particularly in the Pacific Northwest. For both months, the anomalous cold center of the United States is located in the Ohio River Valley, with surface temperatures averaging 5.5 to 6.5 deg°F below normal during SSW.

8

ANOMALOUS UNITED STATES WEATHER PATTERNS ACCOMPANYING STRATOSPHERIC SUDDEN WARMING

A Thesis

by

DONALD ALBERT DOUGLAS

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 1985

Major Subject: Meteorology

ANOMALOUS UNITED STATES WEATHER PATTERNS ACCOMPANYING

STRATOSPHERIC SUDDEN WARMING

A Thesis

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(Head of Department)

May 1985

DEDICATION

This thesis is dedicated to the Glory of God. For as is written in the Gospel of Matthew 19:14, "With God, all things are possible".

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I. INTRODUCTION

Stratospheric Sudden Warming (SSW), first observed and documented by Scherhag (1952), produces large-scale energy and circulation changes in the stratosphere of an amplitude unequaled anywhere else in the atmosphere. Polar regions typically warm by 30° to 50°C (in some cases, over 80°C), the meridional geopotential gradient reverses, and the resultant polar stratospheric circulation becomes easterly. Such is the magnitude of these circulation changes that the stratospheric westerly polar jet (typically of 75 to 100 m/s velocities) completely disappears and is replaced by easterlies.

SSW has been associated with some of the severest winters experienced in the United States in the last three decades. Clearly, the most extreme case was the winter of 1976-1977, the coldest and most severe winter in many locations in a century (Diaz, 1980). Extreme drought in the West and prolonged frigid conditions in the Central and Eastern United States are still in the memory of many people. The headlines of popular news publications highlight the severity of weather conditions: "Snow in Miami!" (The Miami News); "Perverse Weather" (Business Week); "The Deep Freeze! . . . The Mississippi Freezes" (Newsweek).

Most researchers agree that SSW is accompanied by an upward flux of energy and momentum within tropospheric planetary-scale waves, typically blocking ridges. Starr (1976) noted that blocking

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The citations on the following pages follow the style of the <u>Monthly Weather Review</u>.

ridges tended to be present in advance of SSW, whereas Labitzke (1965) observed that the blocking pattern may persist for up to ten days after SSW cessation. The redistribution of energy and the prevalence of persistent large-scale planetary waves suggests that the troposphere mimics the stratosphere during SSW and also undergoes major modifications. However, McInturff (1978) points out that little is known about the attendant tropospheric conditions during SSW. This research will demonstrate that key signatures of tropospheric circulation are significantly affected during SSW.

II. OBJECTIVE

This research examines anomalies in key signatures of tropospheric circulation during stratospheric sudden warming. The primary objective is to determine whether prolonged anomalous weather patterns occur during SSW periods in the contiguous United States. Two data sets are constructed--one representing conditions during sudden warming periods, the other, conditions prevailing during non-warming winter periods. Statistically significant differences between these two regimes are quantified for the following parameters:

A. cyclone frequency and preferred cyclone track location,

B. precipitation distribution, and

C. surface temperature.

Reasons for the observed differences are postulated and certain exceptional sudden warming events are discussed.

III. LITERATURE REVIEW

A. Synoptic Description of SSW

SSW is marked by large-scale and large amplitude changes in the stratospheric thermal and circulation patterns. The stratosphere's normal wintertime state is one with a well-developed quasi-circular vortex with the center at the polar regions. The center of this vortex is a core of extremely cold air (at 10 mb, central temperatures are often as low as -80°C). As SSW commences, warm ridges develop in mid-latitudes and extend into the polar regions, producing an elongation of the polar vortex. The polar vortex eventually splits into two centers, with each center weakening and moving southward. Typically, these two centers move to central Canada and northern Eurasia. Finally, anticyclonic circulation completely dominates the polar regions with easterly circulation becoming established in the northern latitudes in the regions between the polar anticyclone and the southerly displaced polar vortices. The core of the anticyclone over the pole is warm, even warmer than mid-latitude temperatures (at 10 mb, temperatures above freezing have been observed).

Starr (1976) describes the concurrent synoptic conditions in the troposphere associated with SSW. Before SSW, zonal westerlies prevail in the mid-latitudes with a strong vortex situated over the polar regions. At least five days preceeding the split of the stratospheric polar vortex, strong blocking ridges form in the Pacific over, or to the west of, the United States coastline and in the north central Atlantic Ocean. The ridging then extends northwards over

both oceans toward the polar regions. At the same time, the tropospheric polar vortex splits into two distinct centers—one located over the southern Hudson Bay in Canada and the other over eastern Europe. With the strong ridge along the west coast of the United States and the southward-displaced polar low over Hudson Bay, the flow over the United States has a large meridional component. Strong north-northwesterly flow occurs over the western two-thirds of the country with a deep broad trough over the eastern third of the United States (see Fig. 1 which shows the mean monthly 700 mb height field associated with the 1977 SSW).

The magnitude of planetary scale wave anomalies, as depicted in the above tropospheric description should lead to anomalous weather patterns in the United States. Since the geopotential height of any pressure surface is proportional to the vertical mean temperature of the layer between that surface and sea level, the anomalous trough over the United States will result in colder than normal temperature at the surface. Additionally, the strong northwesterly flow will advect additional cold air from northwest arctic Canada to enhance the severity of the anomalously cold air already in the United States and guarantee its persistence. On the other hand, temperature under the ridge in the west, especially in the west coast states, should be warmer than normal.

The precipitation pattern should also be affected by the tropospheric circulation associated with SSW. Cyclones which normally cross the Pacific coast will tend to be turned northward into the Gulf of Alaska. Those storms which track into the west coast should be fairly

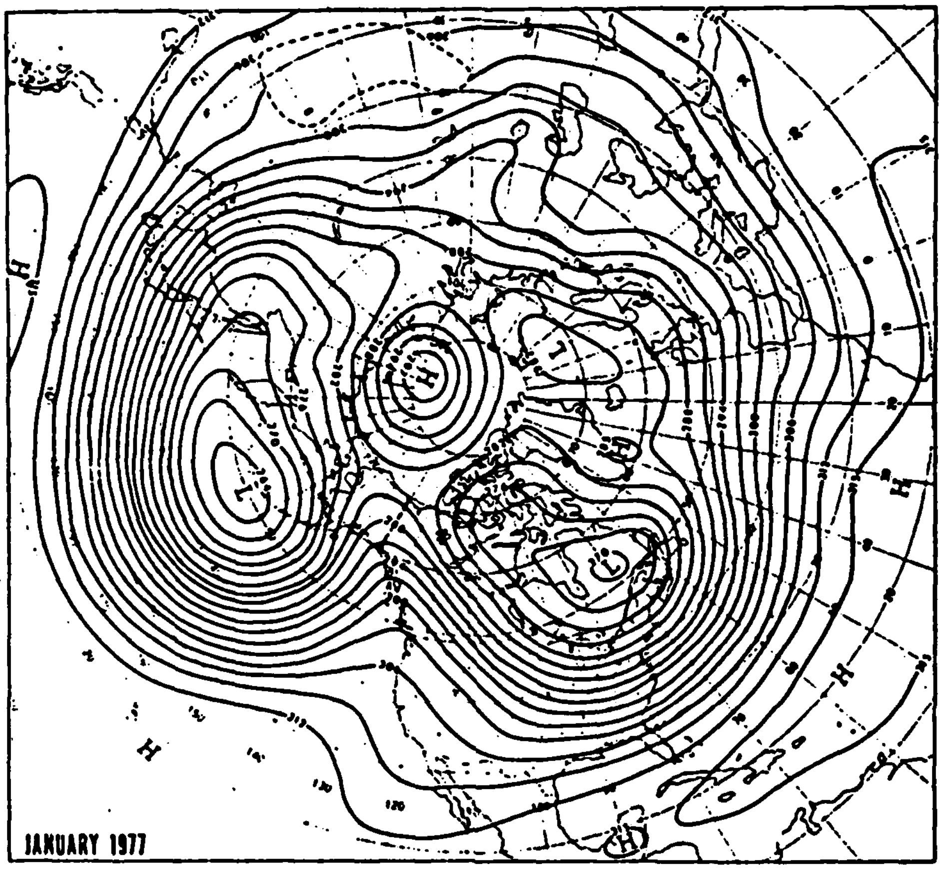

FIG. 1. Mean 700 mb height contours (decameters) for January, 1977(from Wagner,1977).

weak features due to the persistent ridge along the coast. Therefore, the precipitation totals in the west are expected to be less than normal during SSW. Another feature of the expected precipitation pattern is that the general northwesterly wind flow over and to the east of the Rockies will be less humid than normal. The northwesterly flow will eliminate, or at least suppress, warm, moist flow from the Gulf of Mexico, thereby reducing expected precipitation totals for at least the central portions of the United States.

B. Definition and Classification of Stratospheric Warmings

During the years following the discovery of the SSW phenomenon, attempts were made to categorize SSW as major or minor. Some of the events were of sufficient magnitude to produce stratospheric circulation reversals (that is, replacement of the westerly polar night jet with easterly). In other years the temperature disturbance was not sufficient to effect a destruction of the polar night jet. In an attempt to standardize the terminology of SSW, the World Meteorological Organization's Commission for Atmospheric Sciences has adopted the following definitions:

1) A stratospheric warming can be called major if at 10 mb or below the latitudinal mean temperature increases poleward from 60°N <u>and</u> an associated circulation reversal is observed (i.e. mean westerly winds poleward of 60° latitude are replaced by mean easterlies in the same area.

2) A stratospheric warming is called minor if a significant temperature increase is observed in some regions (that is, at least

25°C in a period of a week or less) at any stratospheric level of the wintertime hemisphere; and if criteria for a major warming are not met.

additionally, the SSW circulation configuration eventually decays and the polar stratosphere returns to more normal winter conditions. SSW is distinguished from the "final warming period" in the late spring when the polar stratosphere warms gradually by radiative processes. With this final warming, the westerly polar night jet is gradually replaced by the strarospheric easterly jet which characterizes the summer stratosphere. SSW and the final warming are distinguished from each other by the speed of transition to easterlies. SSW occurs catostrophically in a few days, triggered by dynamical processes; the final warming occurs over a period of weeks, in response to the solar annual cycle.

C. Stratospheric-Tropospheric Coupling

Many studies of SSW energetics have concentrated on stratospheric-tropospheric interaction. Miller (1970), Miller et. al. (1972), Julian and Labitzke (1965), Perry (1967), and Quiroz et. al. (1975) all agreethat the troposphere is the source of energy for SSW, and that SSW is accompanied both by a vertical flux of energy through the tropopause and subsidence in the warm ridges. The loss of energy from the troposphere should result in adjustments to the tropospheric circulation during SSW periods.

Matsuno (1970 and 1971) discusses the importance of the planetary scale waves in a dynamical context. His model successfully simulated the 1963 SSW event. The model was a hemispheric grid point model with 5° horizontal resolution and 19 layers in the vertical. The

lower boundary condition, which was set at tropopause level, was the January 1963 mean height field. Summarized, his model predicts that SSW will occur when there is an appropriate planetary scale disturbance in the troposphere and at a time when the stratosphere is capable of vertical propagation. The stratospheric "index of refraction" is a complicated function of mean zonal wind, mean zonal absolute vorticity, static stability, and zonal wavelength. Under normal conditions, waves will not propagate deeply into the stratosphere, and rather, become trapped in the lower stratosphere. However at times, the wind and thermal field may assume a configuration which will allow propagation at planetary scales. This dynamical process explains why the planetary scales are important in SSW. What Matsuno's theory does not treat, however, is what initiates the tropopause level perturbation and how this perturbation is maintained in the troposhere as its energy is propagated to great heights. What seems to be important, however, is the interaction between the various scales in the troposphere, which organizes itself in such a way that reductions in synoptic scale events are likely to occur simultaneously with amplifications, and possible re-orientations of the planetary-scale ridge-trough configuration.

By means of energetics computations, Perry (1967) described the evolution of the anomalous planetary scale waves in the stratosphere and troposphere. For the 1963 event, conditions started with a growth of planetary wave number two. This wave grew from non-linear interactions with the cyclone scale waves as well as by its own baroclinity. Very large vertical fluxes of potential energy in this

wave into the stratosphere eventually is the mechanism which causes the stratospheric circulation to break down. With the tremendous transfer of energy into the stratosphere in wave number two, it then becomes important to understand how this planetary wave is able to remain large in the troposphere throughout the warming event. Early on, Perry shows the normal cyclone scale waves decay by transfering their energy to the planetary scale. Throughout most of the event, however, the primary mechanism is baroclinic instability on the planetary scale. In fact Wiin-Nielsen (1964) showed that the northward transports of heat and momentum by the cyclone scale waves decrease to almost insignificant amounts, even though the total eddy transports increase significantly during SSW. At the same time the effects of planetary scale waves increase by nearly a factor of two. Thus storms should be diminished by two mechanisms: First, there is less energy to generate them; and second, what baroclinity there is in the troposphere is realized primarily on planetary scale.

Some studies have incidentally included synoptic conditions and subsequent effects in the troposphere. Quiroz (1969) studied the 1966 event and demonstrated that a low 700 mb zonal index appears north of 55°N, and this weak zonal flow occurs simultaneously with the maximum geopotential energy flux through 100 mb. These conditions preceded the warming by 3 - 5 days. Labitzke (1982) presented mean monthly vertical cross sections of temperature and geopotential height at 60°N for the 1970 and 1971 events. Her results revealed both temperature and heights in the lower troposphere that were well below the zonal mean for Canada and Eurasia. However, no statistical

inference was made as to how these values compared to years without SSW. Quiroz (1981) considered the mean zonal flow for the years 1975-1979. His results disclosed that during SSW months, the zonally-averaged polar jet stream was displaced 5° to the south and exhibited speeds 5 m/s faster than climatology expectations. Ramanathan (1977) suggested that once the polar stratosphere warms, the warming process proceeds back to the polar troposphere by radiative transfer. Meridional temperature gradient reversals in the troposphere lead to corresponding circulation reversals in the polar regions; this reversal is associated with a southward displacement of the polar vortex to continental land mass areas of southern Canada and eastern Europe. By this mechanism, the tropospheric circulation and thermal structure mimics the stratosphere during SSW. All of these results suggest modifications in tropospheric circulation and temperature structure during SSW. None, however, directly indicate the magnitude or the statistical significance of anomalous weather patterns due to these changes.

Only a few investigators have focused directly on tropospheric circulation patterns during SSW. Starr (1976), provided a composited description of 500 mb patterns for the SSW cycle based on 12 events. In addition, she presented an evaluation of temperature variance at 500 mb for the period 1955 to 1971. She used the temperature variance as a proxy for hemispherically-integrated energy parameters, specifically available potential energy (the energy available for synoptic-scale systems). She showed that a blocking ridge was present in 11 of the 12 cases of SSW which she considered. During these blocks,

the zonal available potential energy decreased by at least 20%. The anomalous blocking ridge, reduction of the kinetic energy source for storm development, and the onset of SSW should lead to some modification of weather patterns over large geographical areas.

The consequences of blocking in the Atlantic was extensively studied by Rex (1950). Although Rex's study was not associated with SSW in any manner, his observations concerning anomalous weather patterns associated with blocking are most relevant to SSW. Rex, as demonstrated by Starr, found that blocking periods were characterized by: (1) Precipitation totals below normal over continental Europe, Scandanavia and the British Isles; (2) Surface temperatures 2° to 6°C above normal over central and northern Scandanavia; and (3) Surface temperatures below normal over the entire Continent, reaching a minima of 8°C below normal over the Balkan area. Rex's results indicate that significant anomalous weather patterns are associated with blocking. Since SSW and blocking normally occur simultaneously, it follows that blocking-type anomalies should also be observed during SSW.

One significant study of surface temperature over large areas during SSW has been reported. McGuirk (1978) performed an analysis of monthly mean surface temperatures (MMT) for 28 locations in the United States during the SSW events of 1958, 1963, 1971 and 1977. A statistical comparison of the MMTs of these four events with the MMT of 15 years of data not associated with SSW revealed the following: (1) 15 of the stations were significantly colder than non-SSW conditions

at the 95% confidence level; (2) Of the 15 locations, 8 were significantly colder at the 99% level; (3) All of the significantly colder locations were in the Midwest, South and East; (4) 74% of all locations tested were colder than normal and the mean negative anomaly averaged 1.5 standard deviations below normal.

To date, McGuirk's study has been the only attempt to classify surface weather conditions during SSW. No study of a similar nature has been attempted to determine precipitation distribution during SSW. Many studies have been accomplished depicting cyclone frequency (see Klein (1957), Reitan (1974), Zishka and Smith (1980); among others). However, these studies typically have determined mean cyclone frequencies for selected months without attempting to isolate cyclonic activity during SSW periods.

Many of the previous SSW researchers have alluded to tropospheric circulation changes during SSW, but these efforts have usually emphasized planetary-scale features. This present study will show that these planetary-scale anomalies are also accompanied by changes on the synoptic scale. Namely, it will be shown that cyclonic frequency, precipitation and temperature are significantly reduced over large portions of the United States during SSW.

IV. DATA AND ANALYSIS PROCEDURE

A. Periods Selected for Study

As discussed in the previous section, a major SSW is differentiated from a minor event by a temperature gradient reversal of sufficient magnitude to produce a resultant circulation reversal in the stratosphere. It has also been shown that tropospheric circulation mimics the conditions in the stratosphere and also undergoes major circulation modifications. Since the purpose of this study is to determine the effects of modified SSW circulation, major warming events were the only ones selected for the study. Table 1 is a listing of all major events which occurred from 1955 to 1980 as compiled by McInturff (1978) and updated by Quiroz (personal communication). These events are those which fit the World Meteorological Organization's criteria for a major SSW. As discussed by McInturff, it is possible that major warmings in the mesosphere and upper stratosphere may have occurred undetected due to poor stratospheric data coverage if they did not penetrate to low enough elevations. Modern satellite surveillance since the mid 60s has allowed detections of all warmings. Of these major SSW periods listed, nine were during the month of January, eight during February, and only four during December and three in March. The December and March cases constitute too small a sample for statistical inference, so only the months of January and February were selected for the study. Even these samples appear marginal, but they comprise the entire available record.

Table 1. Listing of major SSW events from 1955 to 1980.

Time Period	Duration (days)
22 January 1958 - 12 February 1958	22
18 January 1963 - 6 February 1963	20
19 January 1966 - 27 February 1966	40
17 December 1967 - 15 January 1968	30
17 December 1969 - 4 February 1970	50
7 December 1970 - 24 January 1971	49
4 January 1973 - 6 February 1973	34
15 December 1976 - 10 January 1977	27
13 February 1978 - 5 March 1978	21
15 January 1979 - 5 March 1979	40
10 February 1980 - 7 March 1980	27

The beginning and ending times of the warmings should be taken only as a rough indication of a sudden warming period. The detailed specification of these dates requires consideration of altitude, geographical region, and parameter of interest (e.g., temperature, circulation) (Quiroz, personal communication). Additionally, Labitzke (1965) and Starr (1976) have observed that persistent tropospheric planetary waves are present for considerable periods both before and after warmings. As a result, mean monthly values of cyclone frequency, precipitation and surface temperatures were deemed representative to detect anomalies due to modified tropospheric circulation during SSW. At worst, monthly values represent conservative estimates of the anomalies associated with SSW.

Although, there is some arbitrariness in the definition of what should constitute a SSW, once the definition is fixed, it is objective. The selection of events for this study were taken directly from Quiroz's and McInturff's objective and independent climatologies to guarantee that no bias would enter into the results. The WMO definition has the added advantage that it is based solely on stratospheric criteria; tropospheric anomalies appearing in the present work will not be biased by any tropospheric considerations in the definition of a sudden warming. Therefore, statistical significant results will be related unambiguously to SSW.

Table 2 lists the months that were selected as SSW months. Along with the listing, data are included to provide an estimate of the relative strength of individual warmings. Two indices have been used; the mean monthly 30 mb polar temperature, and the minimum height observed anywhere in the hemisphere of the 30 mb pressure surface; this minimum height will be found in the polar vortex and low values are associated with strong westerlies. The mean 30 mb polar temperatures, is indicative of the thermal intensity of the warming (Labitzke, 1982). The minimum 30 mb height expresses the magnitude of the distortion and weakened intensity of the vortex (Wallace and Chang, 1982). This value reflects a vertical integral of intensity from the surface to 30 mb. The height values in Table 2 reflect the anomaly of the individual event from the mean minimum height for the period 1961 to 1978. Positive values represent a weaker than normal polar vortex (i.e., height above normal) whereas negative values represent a vortex stronger than normal.

Table 2. SSW months and two estimates of their relative intensity. See text for explanation.

Month/Year	30 mb Mean Polar Temperature (°C)	30 mb Anomaly of Minimum Height (decameters)
January 1958	-71	-19
January 1963	-74	27
January 1966	-76	-17
January 1968	-58	58
January 1970	-49	44
January 1971	-54	29
January 1973	-73	8
January 1977	-60	87
January 1979	-75	Not Available
February 1958	-49	-6
February 1963	-52	77
February 1966	-60	57
February 1970	-62	55
February 1973	-44	89
February 1978	-66	50
February 1979	-60	Not Available
February 1980	-70	Not Available

B. Cyclone Fequency and Paths

Cyclone data in this research are based on what is referred to as a cyclonic event, the passage of a surface low pressure center through a perscribed area. Cyclone paths are thus defined objectively and are those published in the Climatological Data, National Summary. These paths are presented in the format shown in Fig. 2. Low pressure centers having at least one closed isobar on a chart analyzed at 4 mb increments and whose lifetimes last at least 24 h are the only

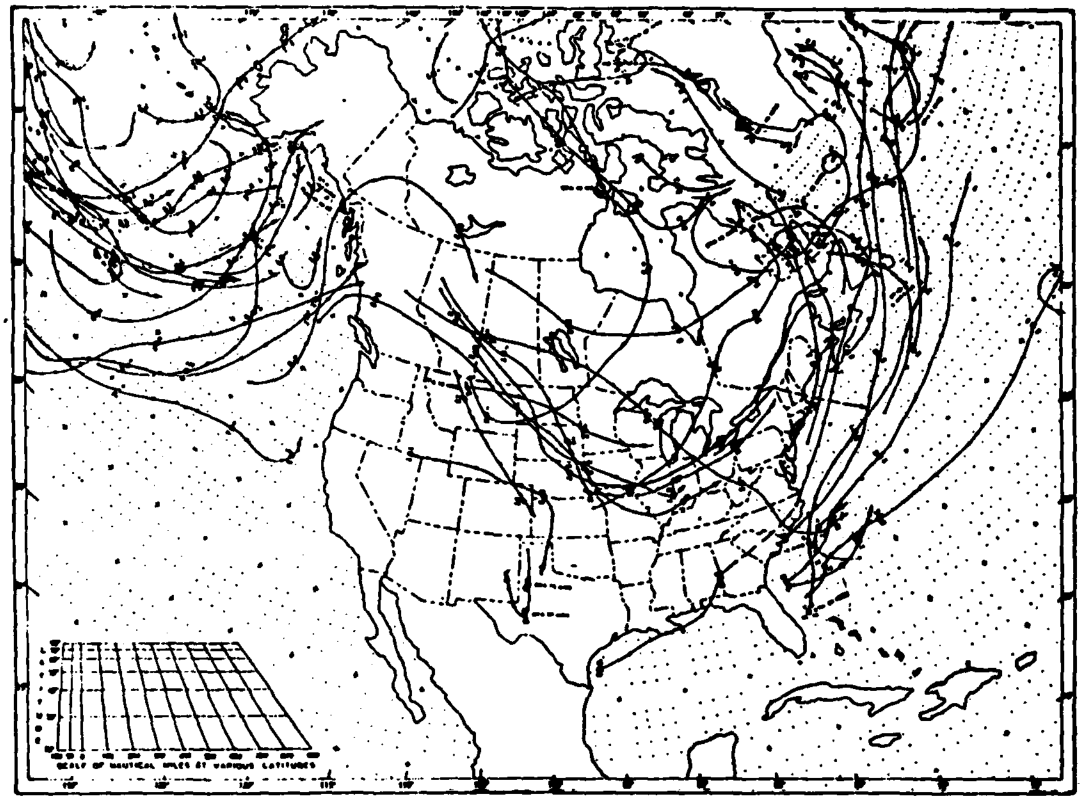

FIG. 2. A sample of the charts used to compute cyclone frequency. Solid lines connect positions of cyclones every 6 hours; therefore, the lines represent cyclone tracks (fron U.S. Dept. of Commerce, 1981).

cyclones included on these maps. The track of the cyclone is determined by a line connecting the position every 6 h.

Reitan (1974) devised a method for determining mean cyclone paths and frequencies. The method utilizes a grid which divides the study area into square boxes measuring 740 km on a side (true at 40°N). A cyclonic event occurs if the center of the low pressure system, as denoted by the storm track, passes through the box. This procedure gives the precise number of cyclone centers that pass through a given box in a month. It does not give a precise measure of storm activity since it treats fast and slow moving cyclones the same, and does not account for the passage of centers in neighboring boxes. Since the base map is not an equal area projection, the frequencies were transformed into frequencies per unit area, relative to a box size of 550,000 km^2 (true at 40°N). Observed monthly frequencies in each box were adjusted by the ratio of areal scale at its latitude to areal scale at 40°N. Fig. 3 shows the grid and areal correction factor for each box. As an example, an observed frequency of 12 events per month at 60°N was adjusted to 9.2 (12 x 0.77) events per 550,000 km^2.

Cyclone frequency was evaluated for each grid box in the array for January and February for each year from 1955 to 1980. The data were divided into two sets: one, the years in which SSW occurred; the other being those years without SSW (hereinafter referred to as non-SSW). The years of SSW events are those listed in Table 1. The mean frequency for each box is determined for both SSW and non-SSW periods.

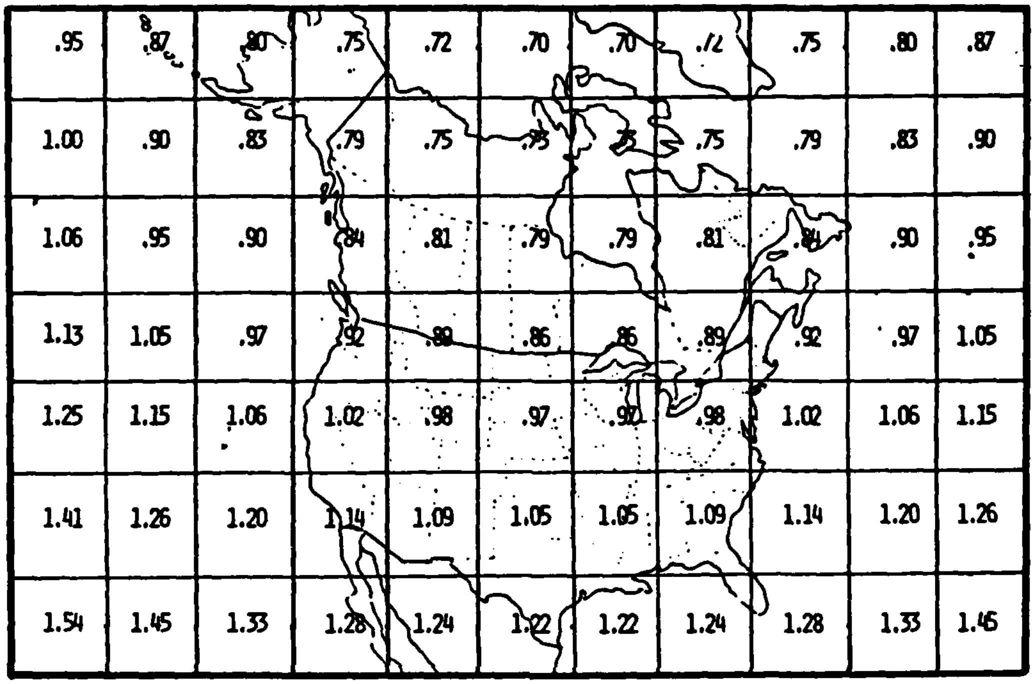

FIG. 3. Area of study and the grid used to determine cyclone frequency. Grid box represents an area of 550,000 km^2, true at 40°N. Numbers are the latitudinal correction applied to cyclone frequency for each grid box.

Over these long periods (8 years of data for SSW and 18 years for non-SSW) the axis of maximum frequency gives a good measure of the mean path of cyclones or mean storm track (Klein, 1957). However, caution must be used in interpreting the axis of maximum frequency for individual months. A comparison of the raw data (Fig. 4 for February, 1963 and the computed frequencies in Fig. 5) reveals that in some areas, the axis of maximum frequency is not necessarily the mean path. For February, 1963, in the eastern Pacific region, the trajectory of the cyclones indicates that most of the storms have an easterly movement and then curve north into the Gulf of Alaska, whereas the analysis of maximum frequency indicates an easterly path into British Columbia. Also for this same month, the axis of maximum frequency extending northward from the New England area indicates a storm path extending north into the Davis Straits. Inspection of the individual cyclone paths show that some of the storms are indeed moving north but others are traveling east and southeast in the same area. However, in many areas, the axis of maximum frequency gives an accurate representation of the trajectory of the storms. Note the areas from central Alberta into the upper Ohio River Valley and the northeast to eastern Canada, and the region east of Florida extending northeast to Labrador. In these two examples, the axis of maximum frequency indicates an accurate measure of both frequency and path. Thus, due to a small sample size for each individual month, the analysis does not necessarily indicate the mean storm path for the month. However, it does indicate the areas of maximum cyclone frequency. When the SSW and non-SSW events are composited over many

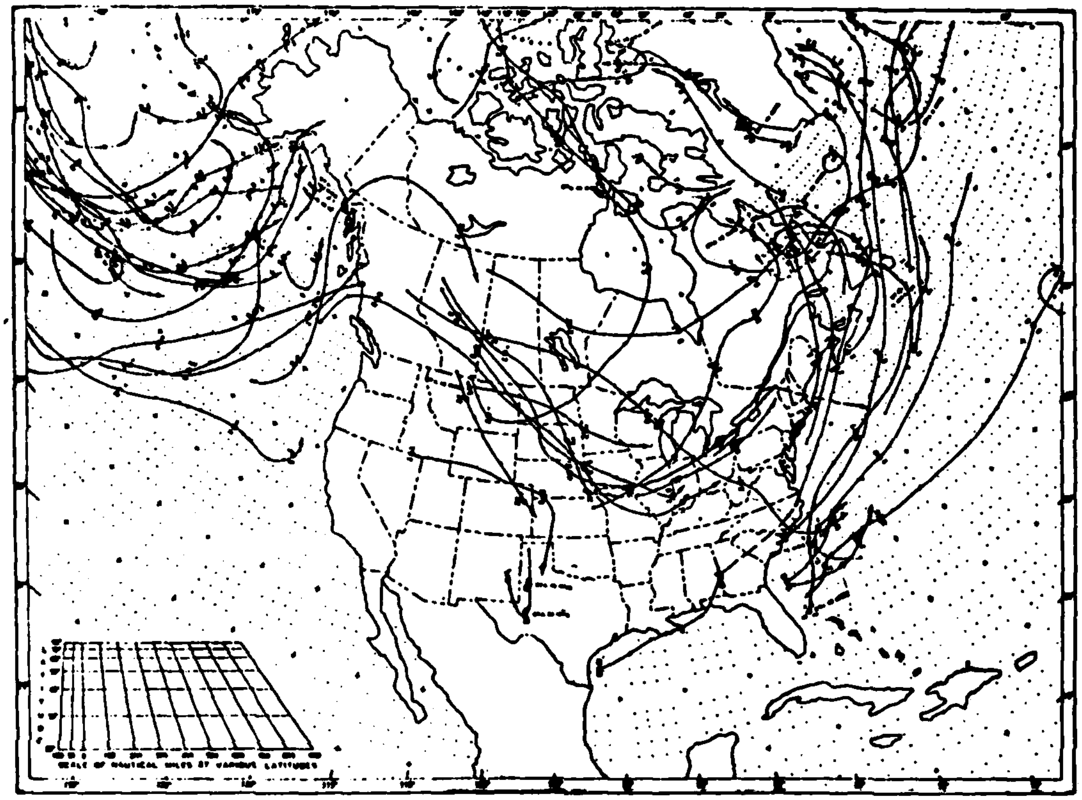

FIG. 4. Cyclone tracks for February 1963. Solid lines connect the cyclone positions every 6 hours (from U.S. Dept. of Commerce, 1981).

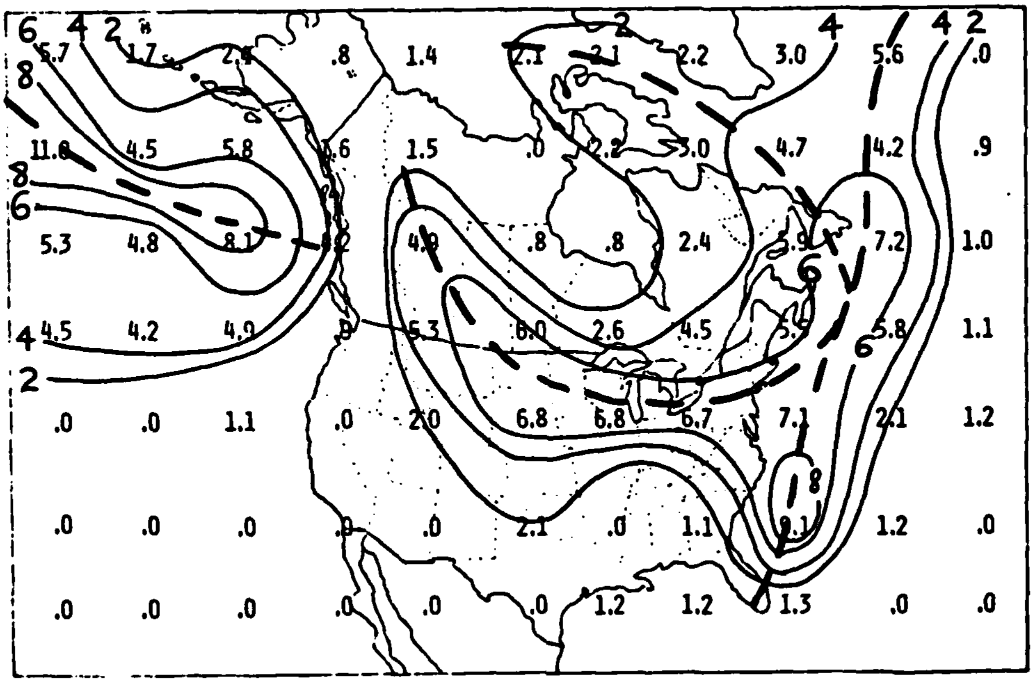

FIG. 5. Computed cyclone frequency for February, 1963. Dashed lines are the axis of maximum cyclone frequency. Isopleth interval is 2 cyclones.

occurrences, the analysis then gives a good measure of both mean cyclone frequency and preferred location and direction of the path of storms.

C. Precipitation and Temperature

The National Climatic Data Center publishes monthly averages of precipitation and temperature for state climatic divisions. These divisions represent regions within a state that are, as nearly as possible, climatically homogeneous. Stations which report both precipitation and temperature are used to calculate the divisional average with each station within a division given equal weight. By 1980, over 5,000 stations were used to calculate the divisional averages in the United States. The state averages for each month are derived from the divisional values by weighting each division by its percentage of the state area (U.S. Dept of Commerce; 1983a,1983b).

The precipitation and temperature averages are presented in units os inches and °Fahrenheit, respectively. Although inconsistent with the current literature procedures, it was decided to retain the reported units for two reasons: (1) Inches of precipitation and °Fahrenheit are still the basis of reporting these parameters among operational weather agencies for the United States; and (2) Climatological studies of United States precipitation and temperature still employ these units, especially whenevaluating data extending decades into the past. As with cyclone frequency, the precipitation and temperature data were divided into the SSW and non-SSW categories for both January and February. For each state, with the exception of the small states Connecticut, Delaware, Rhode Island and Vermont, the

SSW and non-SSW means were statistically compared to detect significant difference between SSW and non-SSW periods. Additionally, the state values for each individual SSW event were compared against the non-SSW state mean in order to determine the pattern of anomalies across the United States for each event.

D. Statistical Methodology

All three parameters (cyclone frequency, precipitation and temperature) were separated into populations of SSW events and non-SSW events to establish mean values for each category. January and February events were grouped individually and treated as independent samples. Although there is some correlation in weather between consecutive months, persistence is a very low skill forecast for monthly mean values, and especially so for precipitation. Thus, January and February samples should be effectively independent, in a statistical sense.

The Student's Two-Sample t-Statistic was used to compare mean values of: (1) cyclone frequency for each grid box; (2) precipiation totals for each state; and (3) surface temperature for each state. Statistical significance of anomalies as estimated with respect to the null hypothesis that the SSW values were less than their non-SSW counterparts. According to Koopmans (1981) the t-statistic has the form:

$$t = \frac{\bar{X}_N - \bar{X}_S}{\left(\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}\right)^{\frac{1}{2}} \left(\frac{1}{n_1}+\frac{1}{n_2}\right)^{\frac{1}{2}}}$$

where:

$\bar{X}_N$ = mean of non-SSW years

$\bar{X}_S$ = mean of SSW years

n_1 = number of non-SSW years

n_2 = number of SSW years

s_1^2 = variance of non-SSW years

s_2^2 = variance of SSW years

Thus, t represents the normalized difference in the means of SSW and non-SSW years. The one-sided statistical difference was tested at the 90% and 99% confidence levels with 24 degrees of freedom. Critical values of the t-statistic for acceptance of the null hypothesis that SSW means are less than those of non-SSW periods are: 90% - 1.31 and 99% - 2.49. Although the purpose of the statistical testing was to detect reductions in SSW parameters, some regions showed increased values of cyclone frequency, precipitation and temperature during SSW. Therefore, these cases were tested for significant increase with the critical t-statistic taking the negative sign.

For each SSW month, each state average of precipitation and temperature was compared to the respective state's non-SSW mean value through the use of the standardized Z-score of the form:

$$Z = \frac{X_i - \bar{X}_n}{S_n}$$

where:

$\overline{X}_n$ = state non-SSW mean

X_i = state SSW value

S_n = state non-SSW standard deviation

Thus, Z is the individual state's SSW temperature or precipitation anomaly given in units of standard deviations above or below normal, with "normal" and "standard deviation" defined by the non-SSW sample.

V. RESULTS

A. Cyclone Frequency

SSW energetics computations (Perry, 1967; Wiin - Nielsen, 1964) have shown that the stratosphere is a sink and the troposphere is a source of energy during SSW. Starr (1976) has also shown that tropospheric available potential energy decreases by at least 20% during SSW events, thereby leading to a dearth of energy for storm development.

To quantify the anticipated reduction of cyclonic activity, cyclone frequencies were compared for SSW and non-SSW periods. The quantities do not indicate the number of cyclones; rather, it counts the number of times that each grid experienced a cyclone. Therefore, by comparing the total number of cyclone events for both SSW and non-SSW periods, a measure of frequency can be ascertained for each category. The results show that cyclone activity during SSW is indeed significantly reduced for both the entire area of study and for the portion of the grid over the United States. Figs. 6, 7, 8 and 9 display the yearly totals of cyclone frequency over the entire grid and over the United States only. The frequency shows large interannual variability for all cases. The SSW years normally stand out as distinct minima, well below the non-SSW mean in most cases, with 1958, 1963 and January 1973 being the exceptions. However, when compared to neighboring values in the decade 1955 to 1965, the 1958 and 1963 events are below the average for the period. Table 3 summarizes cyclone frequency for the period of study.

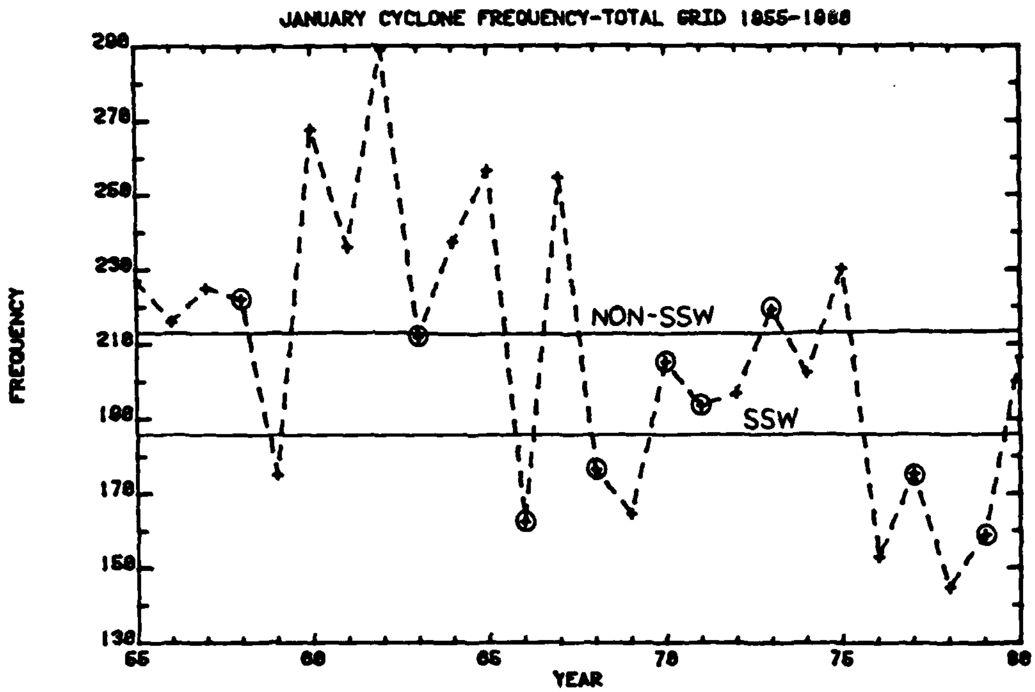

FIG. 6. Yearly January cyclone frequency over North America and adjacent oceans for the period 1955 to 1980. Circled data points are SSW years. Solid horizontal lines are cyclone frequency means for SSW and non-SSW periods.

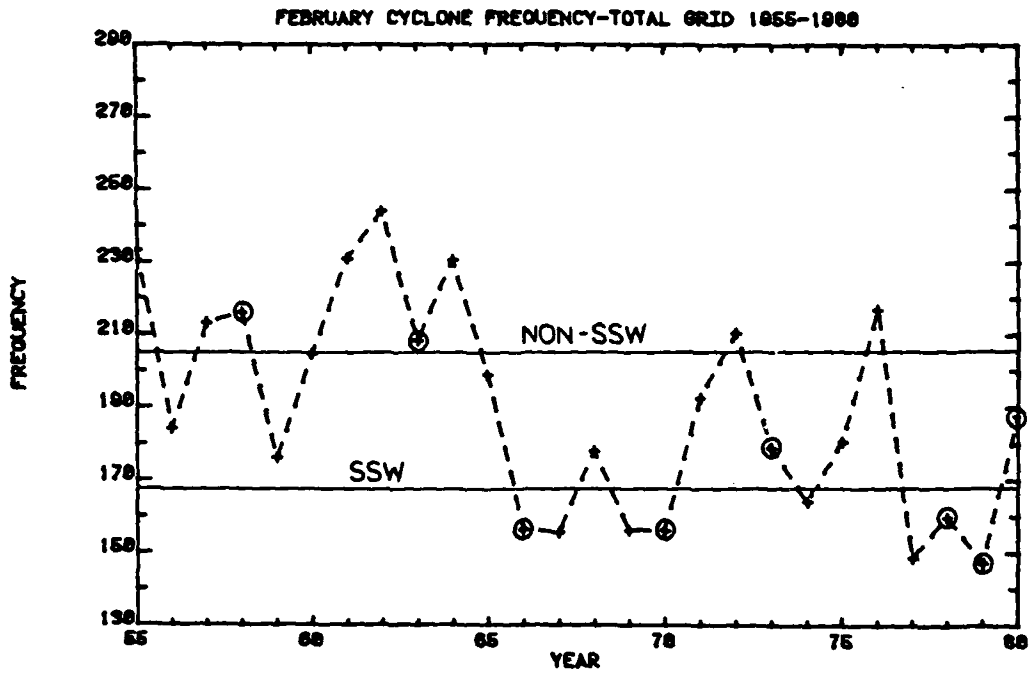

FIG. 7. As Fig. 6, except for February.

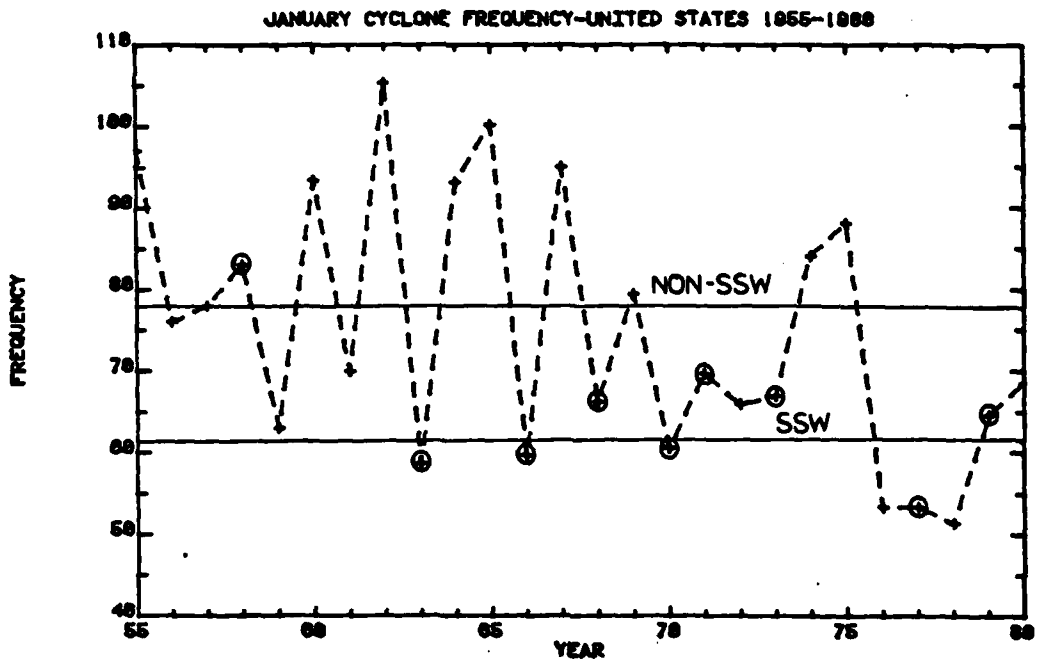

FIG. 8. Yearly January cyclone frequency over the United States for the period 1955 to 1980. Circled data points are SSW years. Solid horizontal lines are cyclone frequency means for SSW and non-SSW periods.

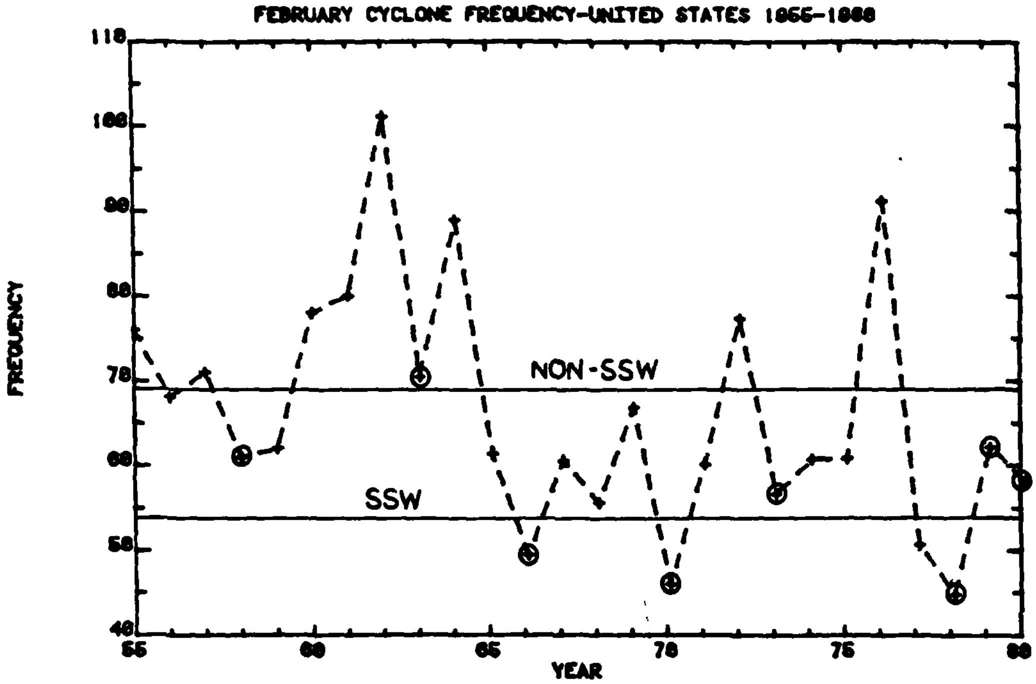

FIG. 9. As Fig. 8, except for February.

Table 3. Comparison of mean cyclone frequency: SSW and non-SSW years - 1955 to 1980.

Region/Month	Number of Events		t-Statistic*	% of Normal Frequency SSW/non-SSW
	SSW	non-SSW		
January:				
Total grid	186.4	212.9	1.69	87.8
U.S.	61.6	78.1	2.70	78.9
February:				
Total grid	167.8	195.6	2.30	85.8
U.S.	54.0	69.3	2.80	77.9

*Critical value of t: 90% - 1.31; 95% - 1.71; 99% - 2.49.

The mean frequencies for SSW events are considerably less than the non-SSW normal for both months. Additionally, the percentage decrease is similar for both January and February indicating a similar reduction of storm activity for both months during SSW. The reduction of cyclone frequency is evident over the entire grid with both months showing significant decreases at the 90% confidence level. The greatest reduction is over the United States where the decrease is significant at the 99% level. The physical significance of this storm reduction will be shown below in the section on precipitation.

In a similar study of cyclone frequency, Zishka and Smith (1980) found that the frequency of cyclones over a similar North American grid has decreased 30% between 1950 and 1978 (Fig. 10). To see if such a trend was evident in this data set, correlation coefficients for a linear regression were computed for cyclone frequencies for both months. Figs. 11, 12, 13 and 14 display the linear regression

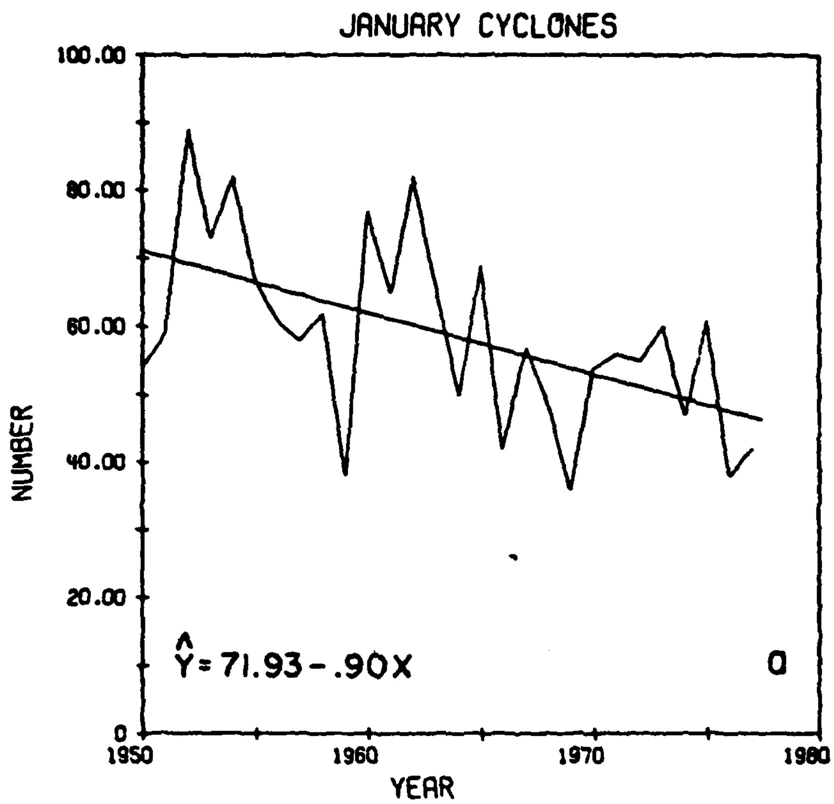

FIG. 10. Yearly variation and corresponding regression line for January cyclones. $\hat{Y}$=number of cyclones; X=year-1950. Correlation coefficient is: r=-0.54(after Zishka and Smith,1980).

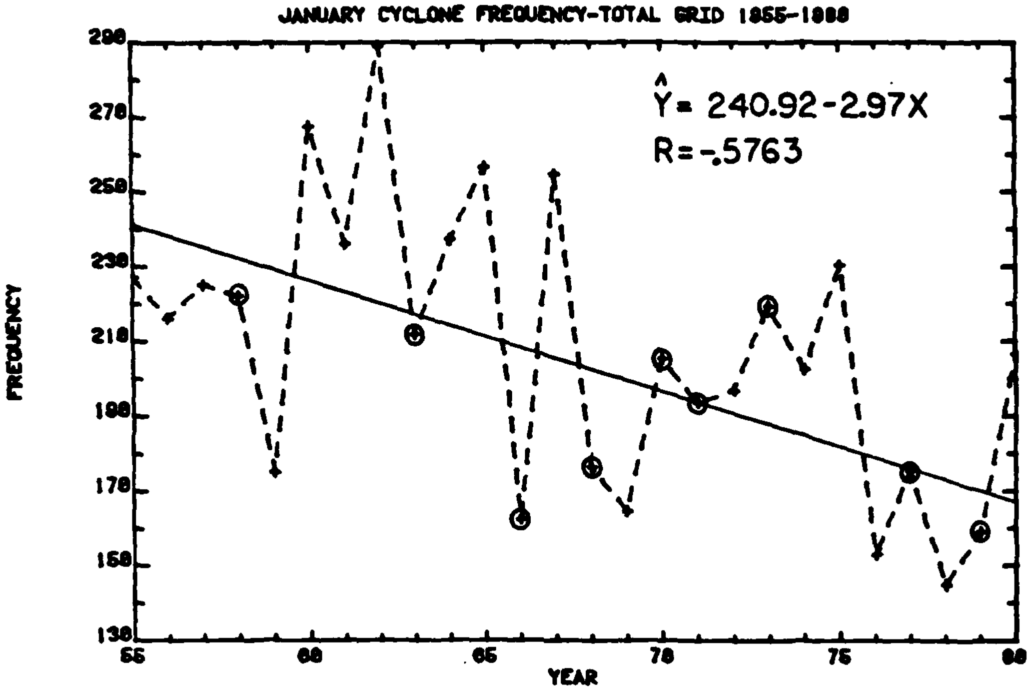

FIG. 11. Yearly cyclone frequency over North America and adjacent oceans, corresponding linear regression line and correlation coefficient. $\hat{Y}$=total number of cyclonic events in all grid boxes; X=year-1955; R=correlation coefficient.

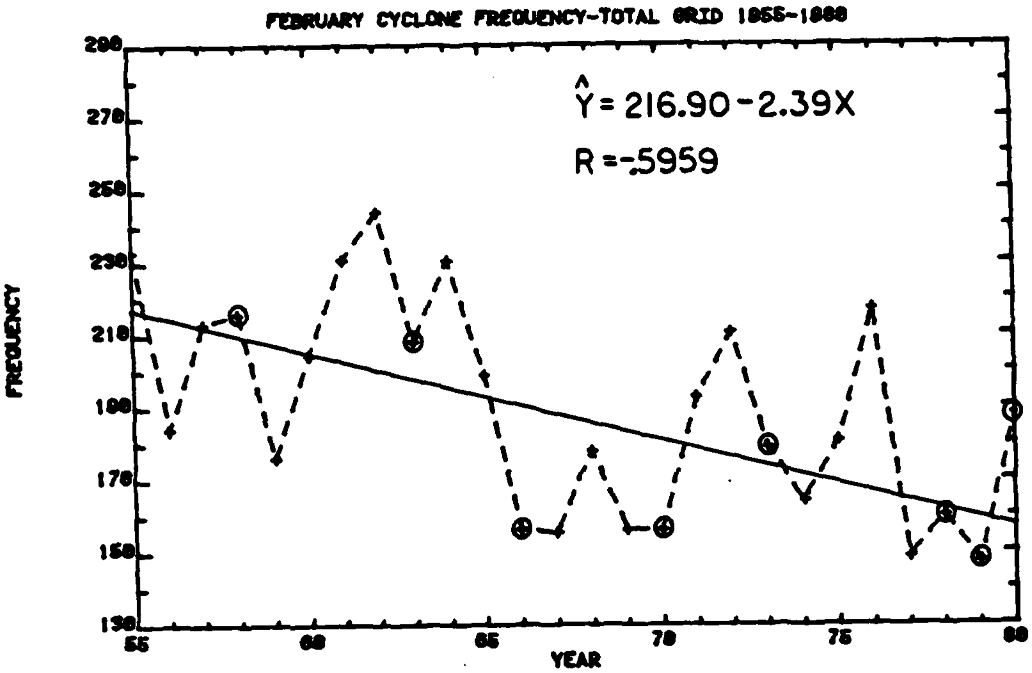

FIG. 12. As Fig. 11, except for February.

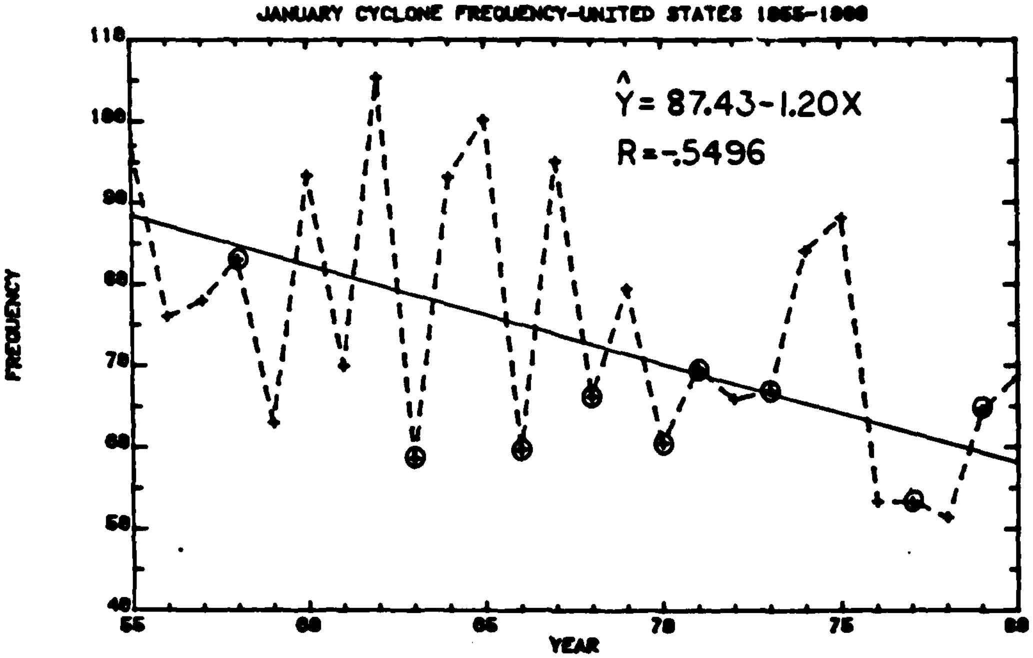

FIG. 13. Yearly January cyclone frequency over the United States, corresponding linear regression line and correlation coefficient. $\hat{Y}$=total number of cyclonic events in United States grid boxes; X=year-1955; R=correlation coefficient.

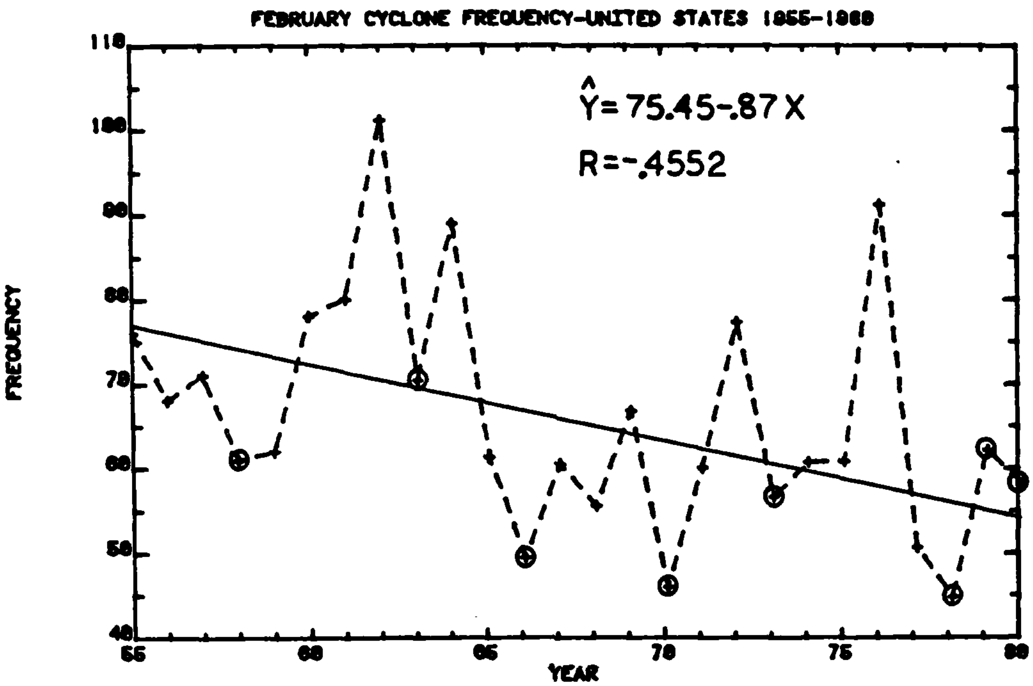

FIG. 14. As Fig. 13, except for February.

and correlation coefficients for January and February, both for the entire grid and the United States portion only. The results showed a similar downward tendency for both months and thus substantiate Zishka and Smith's conclusions. The average decrease in the frequency of cyclonic activity also agreed well with Zishka and Smith's figure of a 30% decrease. The percentage decreases were: January, total grid of 31%; January, U.S. of 35%; February, total grid of 27%; and February, U.S. of 28%.

Zishka and Smith could not document a bias in either data or analysis which could account for the significant decrease in cyclonic activity since the early 50's. It is interesting to note that an inspection of Figs. 11, 12, 13 and 14 show the following: (1) The mean frequency of cyclones is approximately 20% less during SSW; (2) Only three SSW events occurred during the first half of the period, whereas six events occurred during the second half; (3) The majority of SSW events fall below the regression lines. Therefore, it is possible that the cyclone decrease tendency may have a relationship to the occurrence of SSW; specifically, <u>reduced</u> cyclonic frequency occurs in conjunction with <u>increased</u> SSW frequency.

B. Cyclone Distribution and Storm Tracks

Consistent with SSW energetics studies which show that that troposphere gives up energy to the stratosphere during SSW, it has been established that cyclonic frequency is less during SSW. As shown in Chapter III, the planetary-scale tropospheric circulation is also modified. It will now be shown how this modification affects the distribution and preferred paths of cyclones.

Bowie and Weightman (1918) were the first to classify cyclones in the United States by the region where they either first entered the country or by the region where they formed over the United States. Many subsequent studies (Klein, 1957; Reitan, 1974; and Zishka and Smith, 1980; among others) furthur substantiated the validity of the earlier Bowie and Weightman cyclone classification both with respect to location of maximum occurrence and preferred track of storms. Bowie and Weightman's terminology (see Fig. 15) will be used to discuss the differences between SSW and non-SSW storm tracks. Tracks of main interest will be: (1) North Pacific, (2) Alberta, (3) Colorado, (4) South Atlantic, and (5) East Gulf. Although the contiguous United States is the area of interest for this research, cyclonic distribution is shown for the entire North American area.

Figs. 16 and 17 display the mean non-SSW cyclone frequency and paths for January and February. The results for both winter months are nearly identical. Three main storm paths are prominent: (1) the Alberta Low, (2) the Colorado Low, and (3) the South Atlantic Low. Cyclones entering western North America weaken and lose their moisture as they traverse the Rocky Mountains. These cyclones then rapidly intensify in the lee of the Rocky Mountains and become the most prominent United States storm track, the Alberta Low, extending along the United States/Canadian border into the Atlantic Ocean near the Canadian maritime provinces. A second storm track begins in the lee side of the southern Rocky Mountains and extends toward the Great Lakes and into New England. This low pressure center, the Colorado Low, forms under lee side cyclogenetic processes and is an important

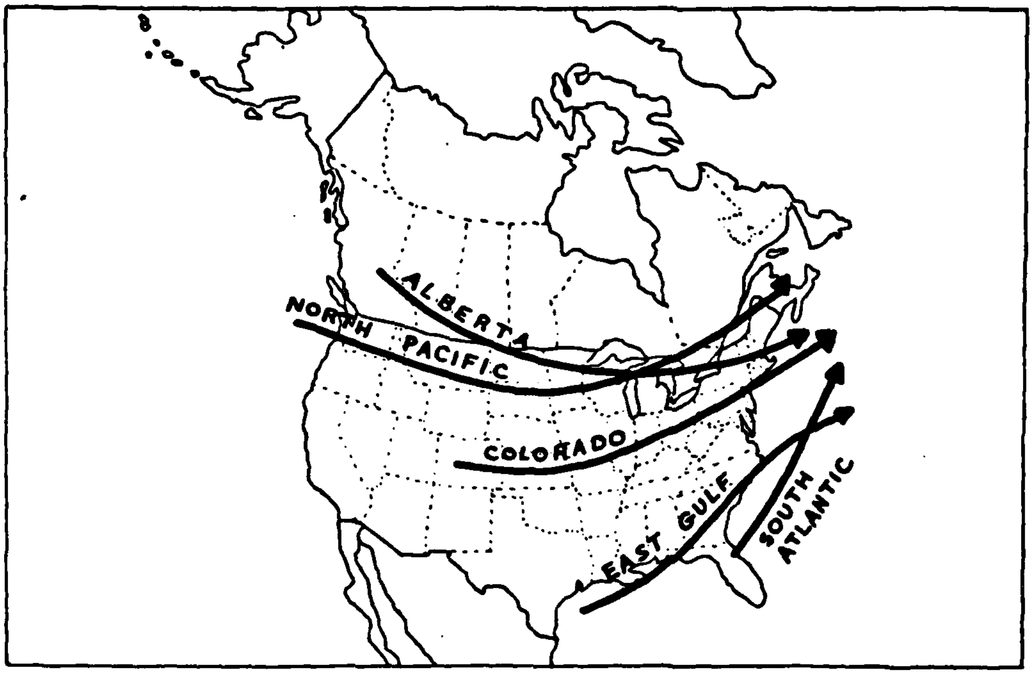

FIG. 15. Principle storm tracks of the United States(after Bowie and Weightman, 1918).

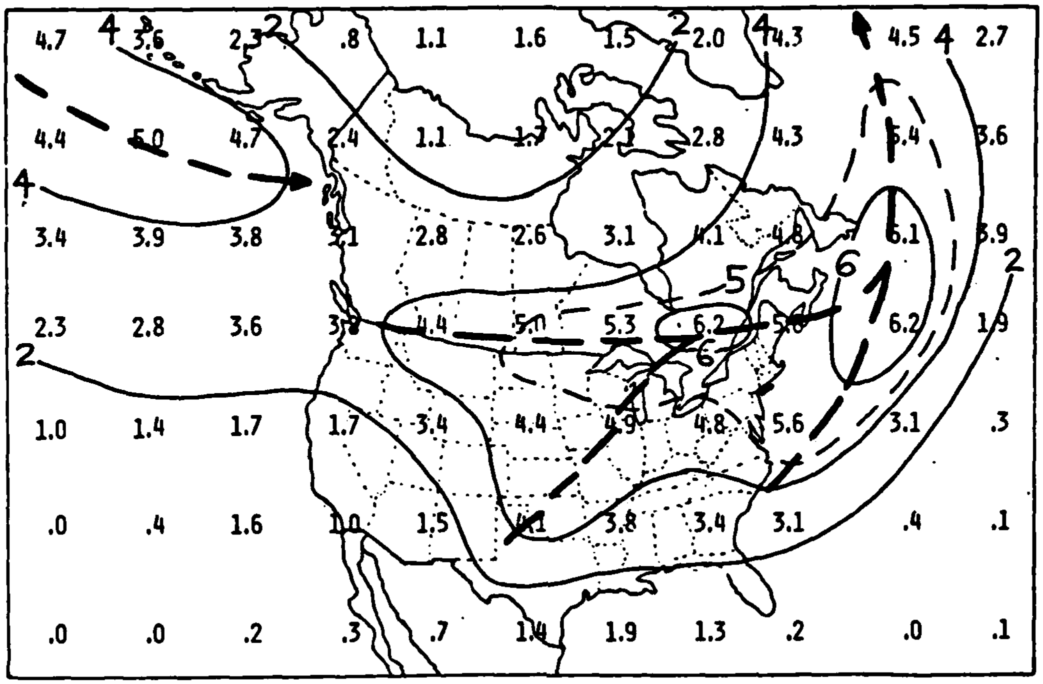

FIG. 16. Mean January storm tracks of non-SSW years for the period 1955 to 1980. Numbers are the mean frequency for each grid box. Dashed lines with arrows indicate the mean storm tracks and the direction of cyclone movement. Isopleth interval is two.

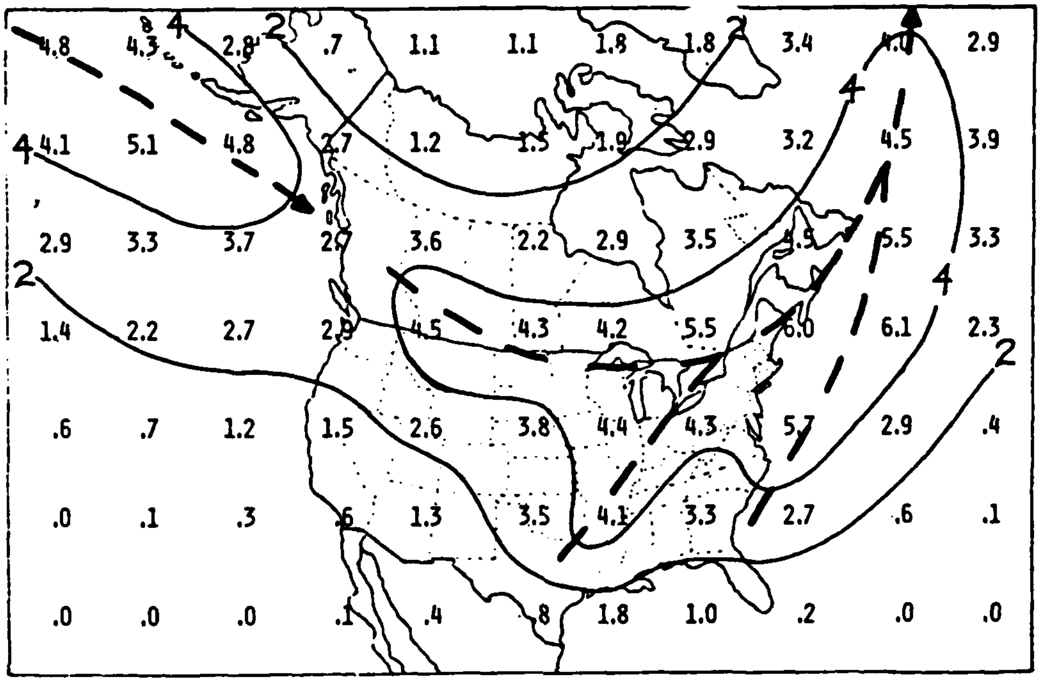

FIG. 17. As Fig. 16, except for February.

contributor to midwest precipitation. Its southerly course allows an entrainment of moisture-laden air from the Gulf of Mexico in advance of the Colorado Low. In fact, Djuric and Damiani (1980) found that the low-level jet forms in conjunction with the Colorado Low and is an important mechanism for supplying water vapor to midwest winter storms. The third most preferred storm track originates in the Atlantic waters east of Florida and extends northeastwards along the Atlantic seaboard. These lows tend to form by diabatic processes as cold continental air flows over the much warmer Atlantic waters.

As shown on Figs. 18 and 19, the mean SSW January and February SSW storm tracks exhibit some similar characteristics; they also exhibit some differences. It has already been shown that cyclonic activity is significantly decreased during SSW. In addition to diminished cyclone frequency, the mean storm tracks also exhibit different patterns.

Storm activity is less prevalent along the Pacific coast. The North Pacific Low does not extend into the United States to merge with the Alberta Low. This absence is totally consistent with the high amplitude planetary-scale ridge, prevalent near the western United States during SSW, which blocks the eastward progression of cyclones into the Pacific Northwest.

The Alberta Low is still a predominant storm track. During SSW, the origin is displaced furthur to the north in Alberta, whereas its path along the Canada - United States border is essentially the same. An anomalous path of the Alberta Low appears in the vicinity of the Canadian maritime provinces. A number of these cyclones curve

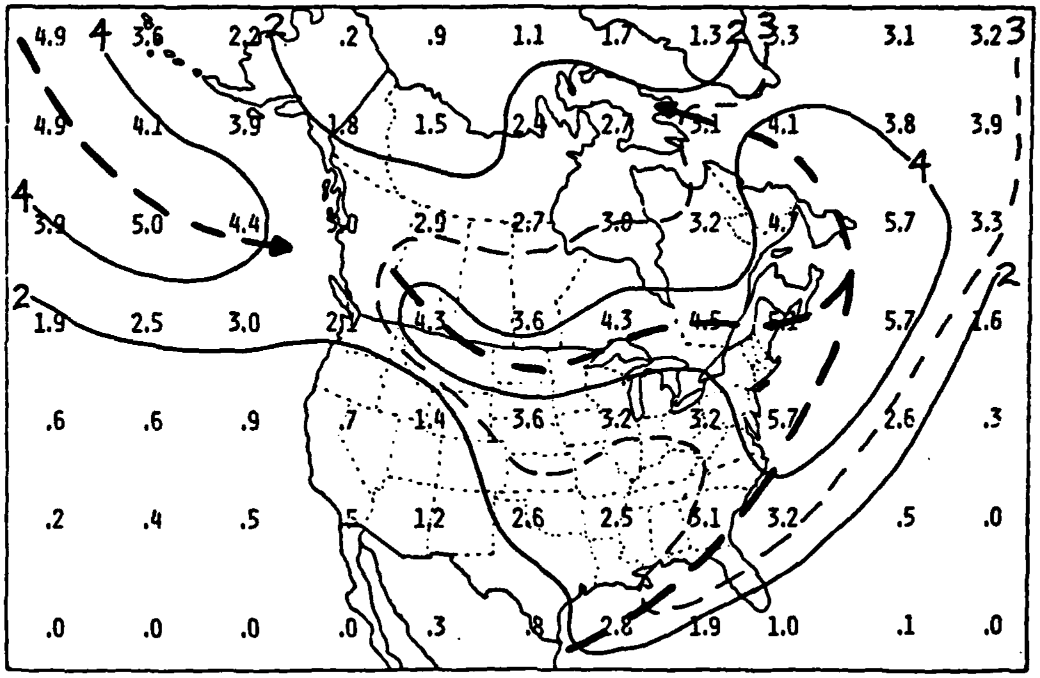

FIG. 18. Mean January storm tracks of SSW years for the period 1955 to 1980. Numbers are the mean frequency for each grid box. Dashed lines with arrows indicate the mean storm tracks and the direction of cyclone movement. Isopleth interval is two.

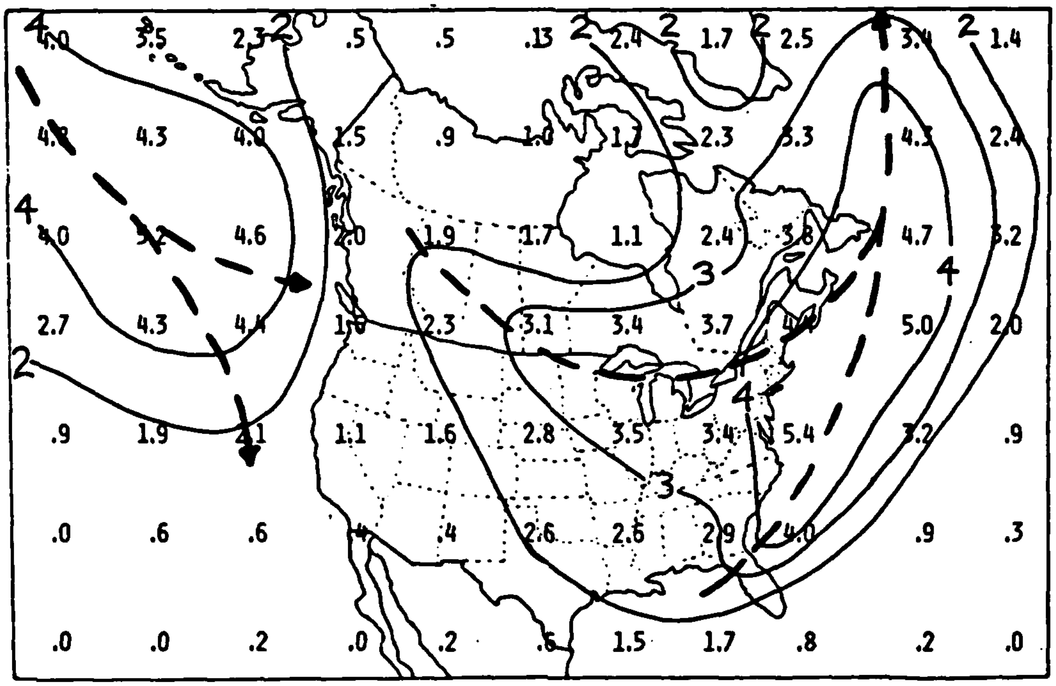

FIG. 19. As Fig. 18, except for February.

northward into the Davis Straits between Canada and Greenland. The origin and subsequent path of the Alberta Low substantiates a major planetary-scale anomaly of SSW; i.e., the polar vortex is displaced southward to the southern Hudson Bay. The southerly displaced polar vortex, along with the blocking West Coast ridge, suggests that the Alberta Lows are formed by cyclogenetic processes along the west side of the displaced vortex and are subsequently steered back to the north by the displaced vortex.

The South Atlantic Low is in approximately the same location. However, the origin of this track extends westward over the Gulf of Mexico, forming the track which Bowie and Weightman (1918) described as the East Gulf Low. This area of increased cyclone frequency over the Gulf of Mexico and the Florida and Georgia coastal waters is a result of an increased northerly flow of cold air over the warm Gulf waters, with the cyclones being formed by diabatic heating of the air mass. The anomalous southern extension of cold air is shown below in the section on surface temperature.

The most striking feature of SSW cyclone distribution is the absence of the Colorado Low as a major feature. The strong ridging along the west coast and over the Rocky Mountains inhibits the progression of troughs across the Rocky Mountains, thereby eliminating the processes for lee-side cyclogenesis. Additionally, the SSW charts (Figs. 18 and 19), suggest that cyclones moving through the lower Midwest United States have more of a southeasterly track than the climatological normal northeast trajectory. The physical significance of the diminished Colorado Low frequency and its relation

to precipitation distribution is discussed in detail in the section on precipitation.

One major difference appears between January and February cyclone frequency. During February, an increase in cyclones occurs off the west coast of the United States. This increase is not apparent during January SSW events. Most SSW events begin in January and end in February. It is hypothesized that the February increase in cyclonic frequency represents the period when SSW begins to break-down. In this phase, the blocking ridge will weaken and move north, allowing the zonal westerly flow to progress eastwards into the western states. Thus, in February, a few storms may move into the United States across California and the southwest states. As shown in the section on SSW precipitation, this increase of cyclonic activity produces anomalously high precipitation in California, Arizona and New Mexico.

Figs. 20 and 21 display the results of the t-test statistics comparing the mean cyclone frequency of each grid box for SSW and non-SSW values. Positive values indicate reduced means during SSW whereas negative values indicate increased cyclone frequency. Inspection of these figures show the following: (1) Cyclone frequency is less over the entire United States except Florida; (2) The enclosed areas (B indicating below normal and A above, significant at 90% confidence level) show that the Pacific Northwest and Midwest states are the areas with the most significant departure from normal. These areas are those most affected by the North Pacific and Colorado Lows; (3) During February, cyclone frequency is above normal over the Pacific Ocean west of the United States; and (4) Cyclone frequency is also

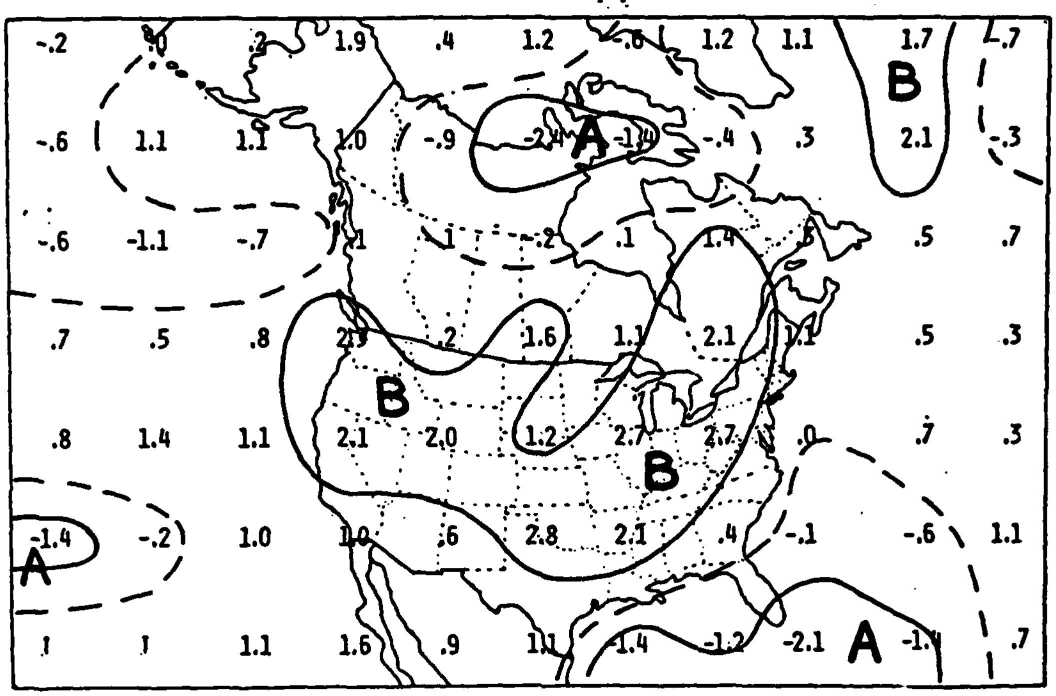

FIG. 20. January Student's t-test statistics comparing SSW cyclone frequency with non-SSW frequency for each grid box. Positive values indicate SSW frequency is less; negative values indicate cyclone frequency is greater during SSW. Dashed lines delineate areas of above and below the non-SSW normal frequency. Solid lines indicate areas of significant difference at the 90% confidence level. Below normal areas are labeled "B", whereas areas above normal are labeled "A".

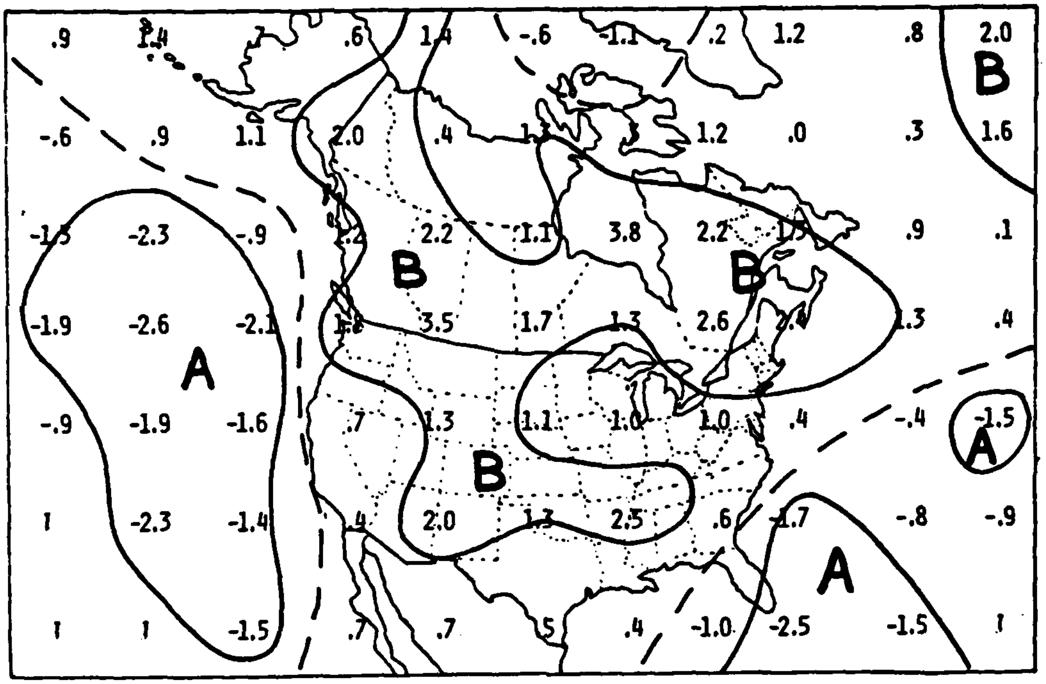

FIG. 21. As Fig. 20, except for February.

above normal over the Gulf of Mexico and waters east of the south Atlantic seaboard states and over north central Canada. The results shown on these two figures furthur verify that cyclone frequency is generally less and modification of planetary-scale features leads to a modification of the synoptic-scale cyclone paths. In the succeeding sections, it is shown how these modifications and cyclone reductions affect the precipitation and temperature distribution in the United States during SSW.

C. Precipitation Distribution

Statistical proof has been established in the previous section that reveals an approximate 20% mean decrease in cyclone frequency over the United States during SSW. Furthurmore, it has been shown that mean storm tracks are modified, especially in the point of origin, and that the Colorado Low becomes almost non-existent as a climatological feature. It is shown in this section how precipitation distribution is affected by these modifications of cyclone development during SSW.

As described in Chapter IV, the state area-weighted precipitation averages were used to compute the SSW and non-SSW means for each state.

The SSW and non-SSW means, standard deviations, and t-test statistics (comparing the two means) are presented in Table 4 for January and Table 5 for February. The critical value of t for acceptance of the null hypothesis that precipitation is less during SSW were respectively: 99% confidence - 2.49; 95% confidence - 1.71; and 90% confidence - 1.31.

Table 4. January SSW and non-SSW precipitation means and standard deviations (units:inches), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower(99%)** ; SSW higher (90%)+ ; SSW higher(99%)++.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic	% SSW / Non-SSW
Alabama	5.16	1.47	5.39	1.80	0.32	96
Arizona	0.86	0.96	1.27	0,95	1.03	68
Arkansas	3.16	1.47	3.39	1.55	0.36	93
California	3.80	1.44	4.37	2.68	0.59	87
Colorado	0.64	0.33	0.89	0.42	1.58*	72
Florida	3.95	1.76	2.82	1.19	-1.95+	140
Georgia	4.67	1.27	4.75	1.74	0.12	98
Illinois	1.46	0.66	2.11	1.14	1.55*	69
Indiana	1.81	0.77	2.70	1.25	1.94*	67
Idaho	2.18	1.19	2.49	0.95	0.72	87
Iowa	0.92	0.50	0.94	0.57	0.09	98
Kansas	0.79	0.59	0.63	0.38	-0.83	125
Kentucky	2.94	1.56	4.08	1.53	1.78*	72
Louisiana	5.07	2.47	4.91	2.26	-0.16	103
Maine	3.60	2.20	2.86	1.35	-1.06	126
Maryland	3.19	1.77	3.13	1.46	-0.09	102
Massachusetts	4.31	3.09	3.38	1.92	-0.94	127
Michigan	1.56	0.41	1.96	0.67	1.62*	79
Minnesota	0.61	0.22	0.85	0.71	0.94	72
Mississippi	5.37	2.46	5.25	2.33	-0.12	102
Missouri	1.67	0.90	1.81	1.04	0.32	92
Montana	0.88	0.41	0.93	0.37	0.28	95
Nebraska	0.51	0.26	0.47	0.26	-0.33	108
Nevada	0.76	0.38	1.01	0.65	1.02	75
New Hampshire	3.60	2.35	2.81	1.54	-1.03	128
New Jersey	3.58	2.35	3.21	1.67	-0.46	111
New Mexico	0.60	0.37	0.60	0.32	-0.01	100
New York	2.73	1.45	2.67	1.16	-0.12	102
North Carolina	4.14	1.14	3.95	1.50	-0.32	105
North Dakota	0.36	0.20	0.49	0.27	1.30	73
Ohio	2.07	0.81	2.65	1.14	1.34*	78
Oklahoma	1.46	0.87	0.99	0.55	-1.67+	147
Oregon	3.91	2.20	4.34	1.60	0.57	90
Pennsylvania	2.83	1.54	2.76	1.32	-0.12	102
South Carolina	4.49	0.93	4.26	1..6	-0.37	105
South Dakota	0.41	0.16	0.36	0.22	-0.48	113
Tennessee	3.74	1.57	4.97	2.16	1.49*	75
Texas	1.85	1.20	1.30	0.56	-1.58+	142
Utah	0.73	0.37	1..2	0.68	1.56*	65
Virginia	3.03	1.40	3.24	1.38	0.35	93
Washington	4.94	2.58	6.03	2.09	1.16	82
West Virginia	2.93	1.40	3.42	1.18	0.94	86
Wisconsin	0.98	0.47	1.12	0.70	0.53	87
Wyoming	0.58	0.20	0.71	0.28	1.19	82

Table 5. February SSW and non-SSW precipitation means and standard deviations (units:inches), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower(99%)** ; SSW higher (90%)+ ; SSW higher(99%)++.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic	% SSW / Non-SSW
Alabama	4.39	2.24	5.31	2.45	0.87	83
Arizona	1.65	1.04	0.70	0.54	-3.08++	235
Arkansas	3.05	1.59	3.82	1.70	1.06	80
California	4.77	2.22	2.93	2.30	-1.90+	162
Colorado	0.69	0.34	0.77	0.27	0.64	89
Florida	3.81	1.28	3.17	1.22	-1.20	120
Georgia	4.40	1.84	4.59	1.78	0.24	96
Idaho	1.68	0.62	1.68	0.63	0.00	100
Illinois	1.15	0.57	2.03	0.64	3.29**	56
Indiana	1.37	0.73	2.59	1.01	3.07**	53
Iowa	0.66	0.33	1.04	0.62	1.62*	64
Kansas	0.72	0.48	0.80	0.56	0.35	90
Kentucky	2.66	1.31	4.12	2.11	1.80*	64
Louisiana	4.71	2.96	4.61	1.72	-0.10	102
Maine	2.46	1.19	2.92	1.25	0.87	84
Maryland	2.92	1.63	3.04	1.43	0.18	96
Massachusetts	2.94	1.14	3.38	1.13	0.91	87
Michigan	0.93	0.21	1.60	0.53	3.43**	58
Minnesota	0.57	0.37	0.69	0.40	0.70	82
Mississippi	4.44	2.54	5.08	2.10	0.66	87
Missouri	1.49	0.79	2.05	0.68	1.84*	72
Montana	0.71	0.25	0.63	0.20	-0.88	113
Nebraska	0.62	0.46	0.63	0.44	0.03	100
Nevada	1.06	0.47	0.77	0.64	-1.111	136
New Hampshire	2.24	1.06	2.94	1.01	1.61*	76
New Jersey	3.22	1.53	3.17	1.16	-0.07	101
New Mexico	0.72	0.26	0.46	0.21	-2.60++	154
New York	2.02	0.72	2.63	0.93	1.69*	76
North Carolina	3.64	1.54	4.07	1.41	0.70	89
North Dakota	0.46	0.29	0.39	0.23	-0.64	117
Ohio	1.49	0.79	2.55	1.10	2.42**	58
Oklahoma	1.32	0.74	1.52	0.66	0.67	87
Oregon	2.96	1.32	2.89	1.24	-0.13	102
Pennsylvania	2.25	0.86	2.72	1.12	1.03	83
South Carolina	3.77	1.66	4.07	1.67	-.43	92
South Dakota	0.52	0.25	0.55	0.35	0.25	94
Tennessee	3.22	1.31	5.02	2.13	2.19*	64
Texas	1.79	0.46	1.55	0.72	-0.85	110
Utah	1.14	0.58	0.89	0.58	-0.99	127
Virginia	2.84	1.42	3.31	1.39	0.78	86
Washington	3.93	1.66	4.24	1.68	0.42	93
West Virginia	2.64	0.96	3.30	1.46	1.16	80
Wisconsin	0.63	0.45	0.99	0.57	1.57*	64
Wyoning	0.52	0.19	0.58	0.16	0.72	91

Figs. 22 and 23 display the areal distribution of January and February SSW precipitation totals expressed as a percentage of the non-SSW mean totals for each state. Over the majority of states, precipitation is less during SSW. During January, 26 of the 44 states considered had below normal precipitation, with 8 of these states significantly below normal at the 90% confidence level. February showed a greater disparity with 31 states below normal. Nine states were significantly drier at the 90% level with 4 of those states below normal at the 99% confidence level. Although the nationwide trend indicates that precipitation is below normal during SSW, the spatial distribution was somewhat different for January and February in all areas except the eastern half of the United States.

During both months, precipitation totals are significantly below normal in the Ohio River Valley states. This pattern of precipitation is a result of the planetary-scale tropospheric circulation during SSW. Northwesterly winds prevail as a result of the large amplitude ridge in the west. Therefore, the general flow from Canada is much drier than normal. Additionally, as shown earlier in the section on cyclone frequency, the Colorado Low becomes a very infrequent climatological feature during SSW as a result of the west coast blocking. The absence of the low precludes the associated flow of moist air from the Gulf of Mexico into the Ohio River Valley ahead of transient low pressure systems. Not only is moisture in short supply, but the lifting mechanism is also more infrequent. Therefore, 30-40% precipitation deficits results.

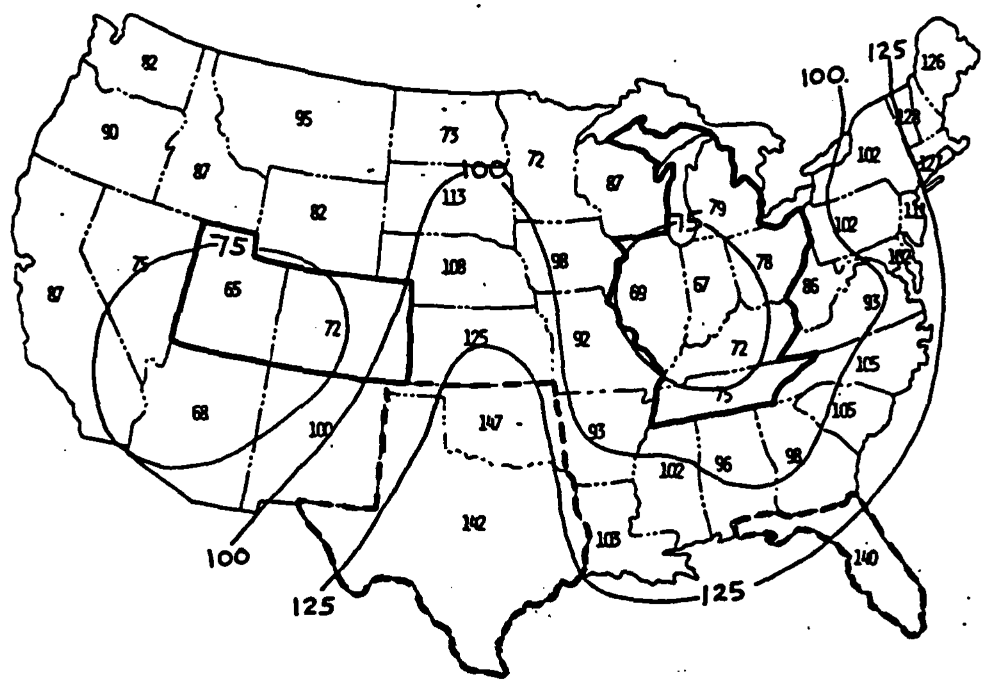

FIG. 22. Ratio of mean monthly January precipitation expressed as percentage (SSW/non-SSW). Isopleths are every 25%. Solid lines enclose areas of significantly reduced precipitation (90% confidence level) and shaded areas within indicate a decrease at the 99% confidence level. Dashed lines enclose areas of significantly increased precipitation during SSW (90% confidence level), and shaded areas within indicate significant increase at the 99% confidence level.

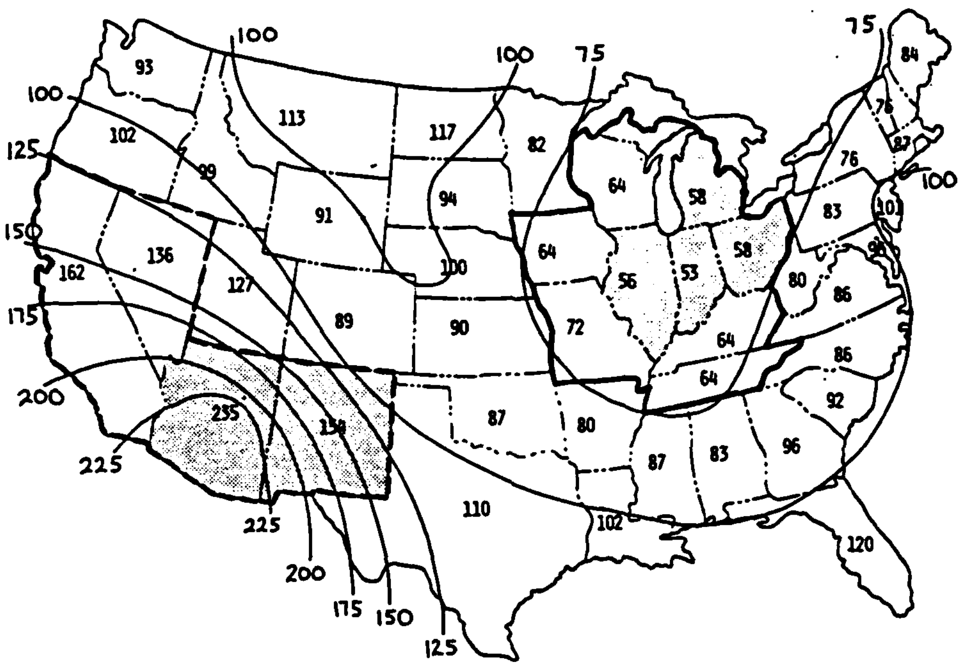

FIG. 23. As Fig. 22, except for February.

The western United States shows a great disparity between January and February. January dry conditions in the west reflect the strong tropospheric ridge along the west coast (as shown in Fig. 1), thus preventing the influx of moisture-laden air from the Pacific Ocean. However, the February precipitation in the West, especially the Southwest, is anomalously high. As hypothesized earlier, this increased precipitation may be the result of the break-down phase of SSW where the blocking ridge along the west coast weakens and moves north, thus allowing moist Pacific westerlies and a few cyclones to protrude into the western states. As shown in Table 6, four of the February cases accounted for most of the anomalous high precipitation in California, Arizona and New Mexico. The February events of 1958, 1973, 1978 and 1980 showed precipitation totals which were one to three standard deviations above the non-SSW normal.

Table 6. February SSW precipitation for California, Arizona and New Mexico. Precipitation is expressed as the number of standard deviations that SSW individual events differed from the non-SSW state mean precipitation.

Year	California	Arizona	New Mexico
1958	+2.1	+1.8	+1.3
1963	+0.3	+0.7	+1.5
1966	-0.4	+0.9	-0.3
1970	-0.4	-0.5	-0.4
1973	+0.9	+2.3	+2.7
1978	+1.1	+3.2	+1.8
1979	+0.8	+0.1	+0.2
1980	+2.0	+3.4	+2.7

Table 7 lists the precipitation summary of the number of states below and above normal during each SSW month studied. (Also, see the appendix for the areal distribution of precipitation for each month). Inspection of the precipitation totals reveals that the 1966 and 1979 events produced at least one standard deviation above the normal for non-SSW years. Furthurmore, the cyclonic frequency (see Appendix) revealed that activity was at or above normal for the southernstates in 1966 and 1979. For these two warmings, only 28 out of 88 states received less than normal precipitation.

For the sake of comparison, the precipitation statistics were re-computed excluding the 1966 and 1979 events. Tables 8 and 9 show the adjusted precipitation data for January and February, respectively. As shown in Figs. 24 and 25, the difference in the statistics is immediately apparent. Although the general pattern remains the same, the number of states with subnormal precipitation greatly increases. During January, 38 of the 44 states had below normal precipitation with 11 of those states significantly below normal at the 90% confidence level. For February, 35 states had below normal precipitation with 21 states significantly below at the 90% confidence level. Seven of the 21 states were below normal at the 99% level. The southwest United States still showed significantly greater precipitation totals.

D. Surface Temperature

The effects of modified tropospheric circulation during SSW are readily apparent in the United States surface temperature distribution. Figs. 26 and 27 display the surface temperature distribution for

Table 7. Summary of precipitation anomalies during SSW months. Columns indicate the number of states (of 44 considered) that differed from the non-SSW mean, and the number that differed by one or more standard deviations.

Month/Year	# Below Normal	# 1 S.D. Below Normal	# Above Normal	# 1 S.D. Above Normal
January 1958	27	5	17	6
January 1963	36	15	8	1
January 1966	22	4	22	4
January 1968	36	5	8	4
January 1970	37	26	7	4
January 1971	27	4	17	4
January 1973	21	2	23	10
January 1977	33	10	11	0
January 1979	6	1	38	22
February 1958	24	8	20	8
February 1963	36	11	8	2
February 1966	19	0	25	10
February 1970	38	12	6	3
February 1973	31	8	13	2
February 1978	30	26	14	11
February 1979	16	0	28	14
February 1980	30	26	14	11

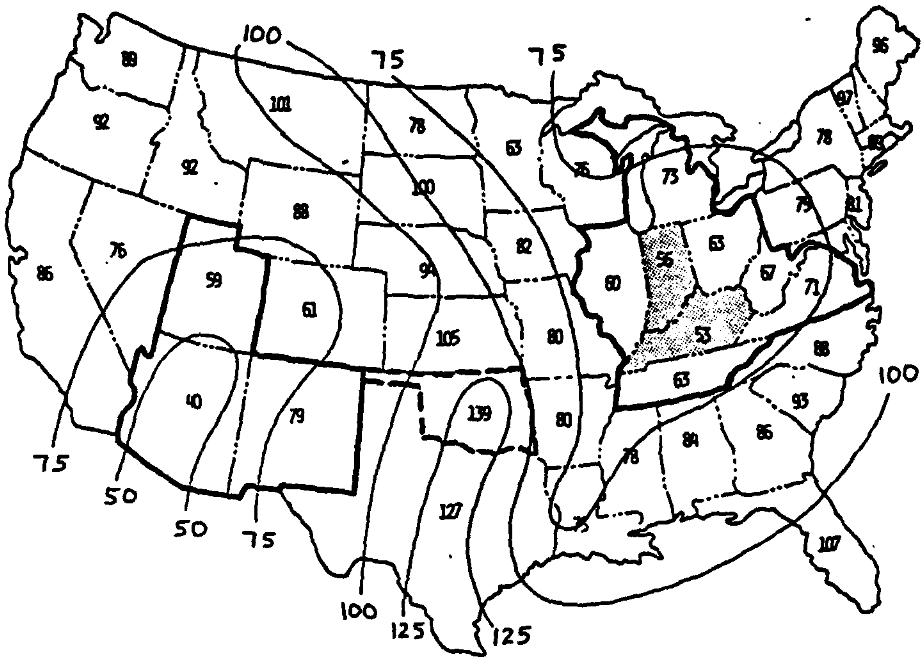

FIG. 24. As Fig. 22, except the 1966 and 1979 events are excluded.

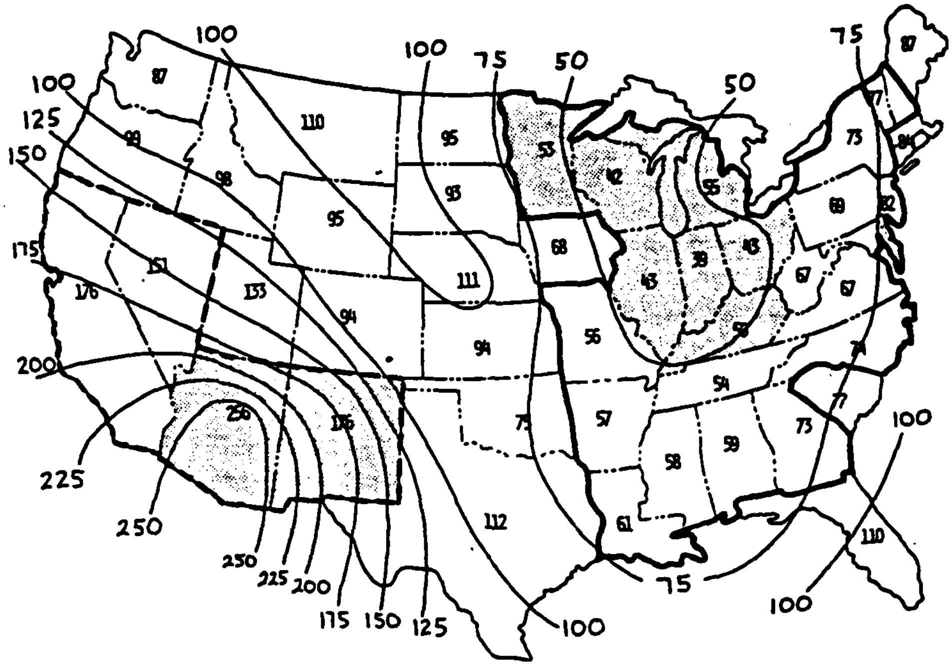

FIG. 25. As Fig. 23, except the 1966 and 1979 events are excluded.

Table 8. January SSW (1966 and 1979 excluded) and non-SSW precipitation means and standard deviations (units:inches), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower (99%)** ; SSW higher(90%)+ ; SSW higher(99%)++.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic	% SSW / Non-SSW
Alabama	4.70	1.23	5.54	1.77	1.14	84
Arizona	0.54	0.41	1.34	1.01	2.01*	40
Arkansas	2.81	1.49	3.49	1.49	1.03	80
California	3.74	1.52	4.33	2.55	0.56	86
Colorado	0.55	0.15	0.90	0.42	2.04*	61
Florida	3.39	1.53	3.14	1.50	-0.37	107
Georgia	4.24	1.07	4.90	1.70	0.95	86
Illinois	1.27	0.46	2.11	1.10	1.92*	60
Indiana	1.54	0.45	2.71	1.21	2.46**	56
Idaho	2.25	1.36	2.43	0.91	0.93	92
Iowa	0.81	0.47	0.98	0.56	0.71	82
Kansas	0.71	0.46	0.67	0.44	-0.19	105
Kentucky	2.24	0.78	4.22	1.50	3.29**	53
Louisiana	4.02	1.52	5.31	2.44	1.29	75
Maine	3.02	1.77	3.15	1.70	0.16	96
Maryland	2.51	0.82	3.39	1.69	1.30	74
Massachusetts	3.41	1.96	3.81	2.54	0.37	89
Michigan	1.45	0.24	1.96	0.66	1.95*	73
Minnesota	0.54	0.17	0.85	0.67	1.16	63
Mississippi	4.41	1.32	5.62	2.55	1.18	78
Missouri	1.50	0.91	1.86	1.01	0.81	80
Montana	0.92	0.46	0.91	0.36	-0.07	101
Nebraska	0.46	0.25	0.49	0.27	0.26	94
Nevada	0.75	0.29	0.99	0.64	0.91	76
New Hampshire	3.02	1.98	3.10	1.86	0.10	97
New Jersey	2.85	1.29	3.52	2.07	0.79	81
New Mexico	0.50	0.26	0.63	0.35	0.91	79
New York	2.23	0.82	2.86	1.34	1.16	78
North Carolina	3.67	0.71	4.14	1.53	0.77	88
North Dakota	0.37	0.22	0.47	0.26	0.88	78
Ohio	1.72	0.43	2.72	1.10	2.30*	63
Oregon	3.96	2.47	4.28	1.56	0.39	92
Pennsylvania	2.25	0.82	2.99	1.49	1.22	75
Oklahoma	1.45	0.98	1.04	0.55	-1.34+	139
South Carolina	4.14	0.70	4.41	1.64	0.41	93
South Dakota	0.38	0.10	0.38	0.22	0.00	100
Tennessee	3.20	1.07	5.04	2.10	2.18*	63
Texas	1.77	1.36	1.39	0.60	-1.01	127
Utah	0.65	0.16	1.10	0.67	1.70*	59
Virginia	2.44	0.66	3.43	1.47	1.70*	71
Washington	5.21	2.68	5.82	2.17	0.59	89
West Virginia	2.38	0.77	3.57	1.26	2.31*	67
Wisconsin	0.87	0.46	1.14	0.67	0.96	76
Wyoming	0.61	0.19	0.69	0.28	0.67	88

Table 9. February SSW (1966 and 1979 excluded) and non-SSW precipitation means and standard deviations (units:inches), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower (99%)** ; SSW higher(90%)+ ; SSW higher(99%)++.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic	% SSW / Non-SSW
Alabama	3.32	0.91	5.56	2.46	2.15*	73
Arizona	1.87	1.12	0.73	0.52	-3.35++	256
Arkansas	2.29	0.83	3.97	1.68	2.32*	57
California	5.25	2.25	2.97	2.22	-2.19+	176
Colorado	0.71	0.40	0.75	0.26	0.34	94
Florida	3.64	1.21	3.29	1.28	0.60	110
Georgia	3.55	1.16	4.82	1.83	1.58*	73
Illinois	0.88	0.27	2.03	0.61	4.37**	43
Indiana	1.02	0.40	2.58	0.95	3.85**	39
Idaho	1.66	0.62	1.69	0.63	0.08	98
Iowa	0.68	0.38	1.00	0.60	1.22	68
Kansas	0.75	0.53	0.79	0.54	0.15	94
Kentucky	2.09	0.89	4.14	1.99	2.41*	50
Louisiana	3.15	0.43	5.09	2.21	2.09*	61
Maine	2.50	1.40	2.87	1.21	0.62	87
Maryland	2.30	1.17	3.22	1.49	1.37*	71
Massachusetts	2.84	1.32	3.37	1.06	1.00	84
Michigan	0.86	0.20	1.55	0.52	3.15**	55
Minnesota	0.39	0.16	0.73	0.40	1.98*	53
Mississippi	3.17	0.67	5.39	2.26	2.33*	58
Missouri	1.17	0.51	2.09	0.68	3.03**	56
Montana	0.71	0.25	0.64	0.21	-0.64	110
Nebraska	0.68	0.50	0.61	0.42	-0.33	111
Nevada	1.17	0.48	0.77	0.61	-1.44+	151
New Hampshire	2.23	1.26	2.87	0.98	1.31*	77
New Jersey	2.72	1.41	3.32	1.21	1.03	82
New Mexico	0.81	0.25	0.46	0.20	-3.44++	176
New York	1.92	0.82	2.62	0.88	1.70*	73
North Carolina	3.10	1.14	4.19	1.38	1.67*	74
North Dakota	0.40	0.20	0.42	0.26	0.18	95
Ohio	1.12	0.44	2.56	1.05	3.23**	43
Oregon	2.90	1.26	2.92	1.26	0.02	99
Pennsylvania	1.92	0.72	2.77	1.07	1.80*	69
Oklahoma	1.17	0.73	1.55	0.66	1.19	75
South Carolina	3.22	1.53	4.20	1.65	1.28	77
South Dakota	0.51	0.29	0.55	0.33	0.29	93
Tennessee	2.70	1.07	5.00	2.02	2.64**	54
Texas	1.78	0.54	1.58	0.68	-0.64	112
Utah	1.20	0.67	0.90	0.55	-1.10	133
Virginia	2.29	1.12	3.43	1.37	1.83*	67
Washington	3.73	1.44	4.27	1.72	0.69	87
West Virginia	2.27	0.79	3.34	1.39	1.77*	67
Wisconsin	0.43	0.28	1.02	0.54	2.50**	42
Wyoming	0.54	0.23	0.57	0.16	0.29	95

January and February, respectively. SSW mean monthly temperatures for each state are expressed as the departure from the non-SSW mean value (negative being below the normal: positive above). During January, 43 states were below normal with Nevada being the only exception. Thirty-three states were significantly colder at the 90% confidence level, and 20 of the 33 were significantly below normal at the 99% level.

As with the precipitation distribution, February showed a somewhat different spatial temperature distribution than January. Like January, the coldest anomalies in February were in the Ohio River Valley and becoming warmer toward the west. However, the February SSW temperatures become warmer than normal from the Rocky Mountains westward to the Pacific coast reaching temperature significantly above normal at the 90% confidence level in Idaho, Oregon and Washington. As with the precipitation distribution, the February anomalies are the result of the milder Pacific westerlies protruding into the west as the SSW phenomena decays.

The significantly colder temperatures east of the Rocky Mountains correspond well with the cyclone and precipitation distributions discussed earlier. First, the below normal temperatures substantiate the highly meridional pattern during SSW with a strong ridge in the west and the extension of the southerly displaced polar vortex in the east. This pattern produces an anomalous cold flow of air extending even into the Gulf Coast states. This type of flow produces two major consequences consistent with the findings of this research.

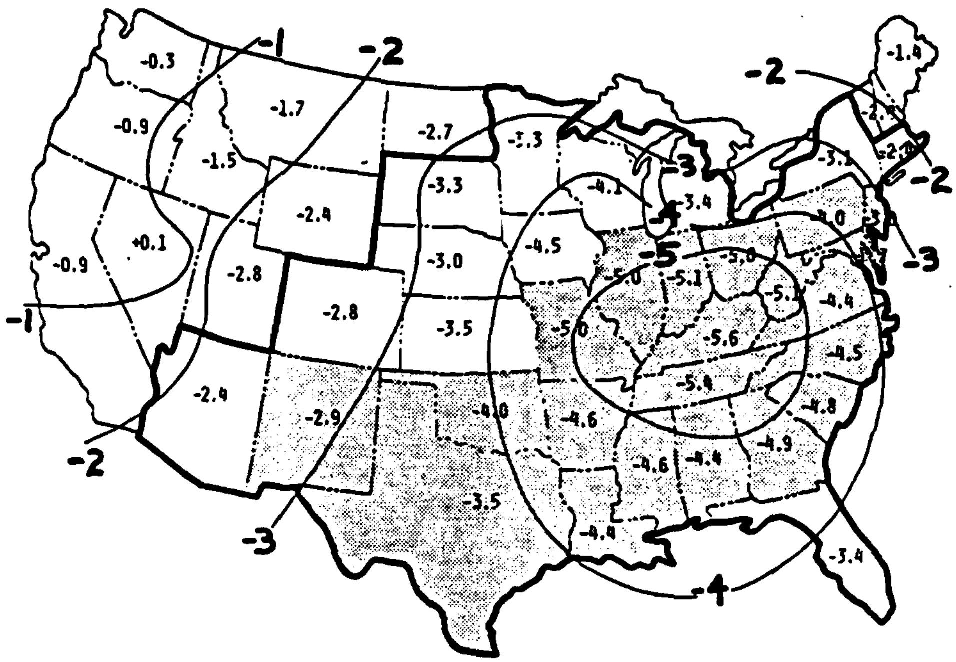

FIG. 26. Difference between mean SSW and non-SSW January surface temperature(°F). Negative values indicate SSW temperatures are lower than non-SSW, and vice versa. Solid lines enclose areas of colder SSW temperature (90% confidence level) and shaded areas within indicate colder temperatures at the 99% confidence level. Dashed lines enclose areas of warmer SSW temperatures (90% level). Isopleth interval is 1°F.

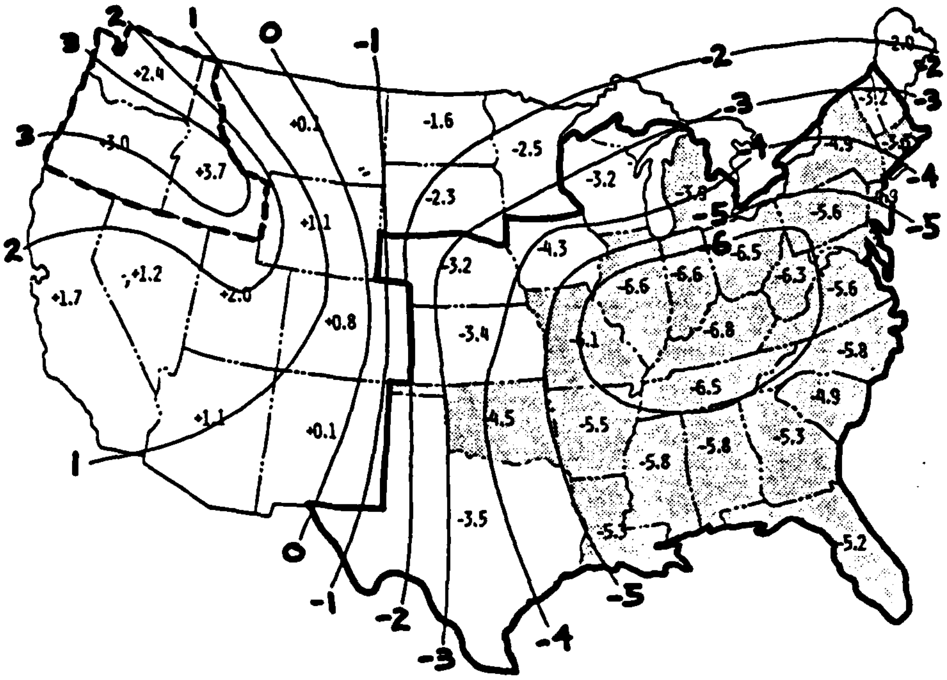

FIG. 27. As Fig. 26, except for February.

First, the general air flow is considerably less humid in origin and the advection of warm, moist air from the Gulf of Mexico is greatly suppressed. Secondly, the anomalous flow of cold air over the Gulf of Mexico and Atlantic waters of Florida and Georgia substantiate the increased cyclogenesis by diabatic processes.

For completeness, Tables 10 and 11 list the SSW and non-SSW temperature data for the United States.

Table 10. January SSW and non-SSW surface temperature means and standard deviations (units:°Fahrenheit), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower(99%)**.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic
Alabama	40.5	3.50	44.9	4.28	2.67**
Arizona	39.5	1.77	41.9	2.71	2.39*
Arkansas	35.4	4.49	40.0	3.25	2.96**
California	43.4	1.61	44.2	2.28	0.91
Colorado	21.4	3.89	24.2	2.95	2.06*
Florida	55 4	3.10	58.8	4.22	2.17*
Georgia	42.3	3.27	47.2	4.47	2.85**
Illinois	20.9	6.33	25.9	3.98	2.50**
Indiana	21.8	5.91	26.9	3.67	2.72**
Idaho	21.7	4.63	23.2	3.92	0.82
Iowa	13.9	6.41	18.4	4.09	2.18*
Kansas	25.7	5.35	29.2	3.87	1.90*
Kentucky	28.6	4.66	34.2	4.03	3.20**
Louisiana	45.0	3.42	49.4	3.93	2.86**
Maine	13.6	5.15	15.0	3.99	0.80
Maryland	29.5	3.66	33.2	3.30	2.64**
Massachusetts	22.8	4.50	25.2	3.18	1.58*
Michigan	16.4	4.73	19.8	3.12	2.19*
Minnesota	4.6	7.43	7.9	3.96	1.48*
Mississippi	40.6	3.56	45.2	3.93	2.98**
Missouri	25.1	5.79	30.1	3.79	2.63**
Montana	15.6	6.88	17.3	5.90	0.63
Nebraska	19.9	5.96	22.2	4.10	1.54*
Nevada	30.4	3.58	30.3	3.85	-0.05
New Hampshire	16.6	4.56	18.6	3.57	1.24
New Jersey	27.7	4.08	30.7	3.18	2.07*
New Mexico	32.0	2.04	34.9	2.70	2.67**
New York	18.1	4.36	21.2	3.46	1.94*
North Carolina	36.7	3.20	41.2	3.83	3.00**
North Dakota	4.0	8.06	6.7	5.41	0.98
Ohio	22.5	5.24	27.5	3.72	2.80**
Oklahoma	33.5	4.70	37.5	3.54	2.42**
Oregon	31.3	4.13	32.0	3.58	0.47
Pennsylvania	22.2	4.48	26.2	3.43	2.53**
South Carolina	40.6	3.16	45.4	4.29	2.95**
South Dakota	12.4	7.19	15.7	5.22	1.31*
Tennessee	32.1	4.13	37.5	3.98	3.25**
Texas	42.4	3.58	45.9	2.90	2.68**
Utah	23.5	4.25	26.3	3.95	1.67*
Virginia	31.3	3.38	35.7	3.59	2.99**
Washington	29.7	4.41	30.0	4.43	0.15
West Virginia	26.0	4.01	31.1	4.06	3.04**
Wisconsin	9.7	6.59	13.8	3.87	2.02*
Wyoming	17.2	5.52	19.6	3.56	1.31*

Table 11. February SSW and non-SSW surface temperature means and standard deviations (units:°Fahrenheit), and t-statistics. Confidence levels comparing SSW to non-SSW means are denoted by the following symbols in the t-statistic column: SSW lower(90%)* ; SSW lower(99%)** ; SSW higher (90%)+ ; SSW higher (99%)++.

State	SSW Mean	SSW S.D.	Non-SSW Mean	Non-SSW S.D.	t Statistic
Alabama	42.9	2.84	40.7	4.59	3.29**
Arizona	45.8	3.43	44.7	3.41	-0.72
Arkansas	39.0	3.44	44.5	3.58	3.62**
California	48.8	3.09	47.1	2.39	-1.59+
Colorado	28.3	4.00	27.5	3.96	-0.45
Florida	55.3	2.41	60.7	3.89	3.62**
Georgia	44.6	2.34	49.9	4.39	3.22**
Idaho	30.8	3.54	27.1	3.68	-2.38+
Illinois	24.3	5.40	30.9	3.22	3.87**
Indiana	24.1	5.39	30.7	3.32	3.87**
Iowa	19.4	5.46	23.7	4.12	2.21*
Kansas	31.0	5.72	34.4	4.22	1.68**
Kentucky	30.9	4.17	37.7	4.19	3.82**
Louisiana	47.6	2.51	52.9	4.28	3.25**
Maine	14.6	2.77	16.6	3.86	1.30
Maryland	29.9	3.86	35.4	2.96	4.01**
Massachusetts	23.0	3.24	26.6	2.98	2.79**
Michigan	17.2	3.99	21.1	3.17	2.66**
Minnesota	10.7	3.86	13.2	4.87	1.25
Mississippi	43.3	2.82	49.1	4.53	3.33**
Missouri	29.1	4.80	35.2	3.31	3.76**
Montana	23.6	5.10	23.5	5.50	-0.05
Nebraska	17.3	3.16	20.5	3.44	2.23*
Nevada	35.6	4.72	34.4	3.45	-0.70
New Hampshire	17.3	3.14	20.5	3.44	2.25*
New Jersey	27.8	3.87	32.6	2.76	3.63**
New York	17.9	3.83	22.8	3.25	3.40**
New Mexico	38.1	2.81	38.0	3.92	-0.07
North Carolina	38.1	2.75	43.9	4.39	3.42**
North Dakota	10.6	6.01	12.4	5.26	0.80
Ohio	23.9	5.03	30.4	3.45	3.83**
Oklahoma	38.1	3.61	42.6	3.78	2.57**
Oregon	39.0	2.98	36.0	2.92	-2.33+
Pennsylvania	22.5	4.12	28.1	3.04	3.87**
South Carolina	43.8	2.39	47.7	3.91	3.30**
South Dakota	18.7	6.62	21.0	5.15	0.98
Tennessee	34.5	3.73	41.0	4.48	3.55**
Texas	46.5	2.74	50.0	3.64	2.39*
Utah	32.5	4.74	30.5	4.12	-1.05
Virginia	32.4	3.25	38.0	3.30	4.02**
Washington	37.3	2.87	34.9	3.32	-1.74+
West Virginia	27.4	4.13	33.7	4.02	3.63**
Wisconsin	14.7	3.95	17.9	3.90	1.92*
Wyoming	24.6	4.41	23.5	3.69	-0.63

VI. CONCLUSIONS

For the period 1955 to 1980, mean monthly values of cyclone frequency, precipitation and surface temperature were studied over the continguous United States during the months of January and February during years in which major Stratospheric Sudden Warming (SSW) occurred. Based upon a statistical analysis comparing SSW events against a climatological base of years with no SSW occurrences, the following conclusions are drawn:

A. Cyclone frequency is diminished by approximately 22% during both SSW months. This reduction is consistent with energetics considerations that the troposphere gives up energy to the stratosphere during SSW. The areas of the greatest cyclone reduction are the Pacific Northwest, the southern central, and the Ohio River Valley states.

B. Two storm tracks are dominant during SSW. However, both of these major storm tracks are altered slightly in point of origin and frequency of occurrence. First, the Alberta Low originates further to the north in Alberta. Secondly, the Atlantic Low's point of origin occurs further westward over the Gulf of Mexico and then extends northeastward along the Atlantic seaboard. The most notable finding of United States cyclone paths is the almost total lack of the Colorado Low as a climatological feature from the southern Rocky Mountains to New England.

C. SSW monthly precipitation totals were significantly below normal in the central northern United States, with the Ohio River Valley states exhibiting the most significant departures from normal.

During February, the southwest states showed significantly higher precipitation totals. It is suggested that these higher totals are a reflection of the termination of SSW, when the west coast blocking ridge begins to dissipate allowing Pacific westerlies to protrude into the western United States.

D. Surface temperatures were significantly below normal in most states east of the Rocky Mountains for both months. Below normal temperatures extended all the way to the west coast in January. During February, temperatures were above normal from the Rocky Mountains westward to the Pacific coast.

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APPENDIX

The distribution of precipitation, surface temperature and cyclones are displayed for every SSW month studied in this research. For each SSW month of January and February, the individual state's monthly precipitation and surface temperature anomaly is given in units of standard deviations above or below the non-SSW mean value. Cyclone frequency for each SSW month is displayed for the entire grid area. The axis of maximum cyclone frequency is highlighted.

APPENDIX

The distribution of precipitation, surface temperature and cyclones are displayed for every SSW month studied in this research. For each SSW month of January and February, the individual state's monthly precipitation and surface temperature anomaly is given in units of standard deviations above or below the non-SSW mean value. Cyclone frequency for each SSW month is displayed for the entire grid area. The axis of maximum cyclone frequency is highlighted.

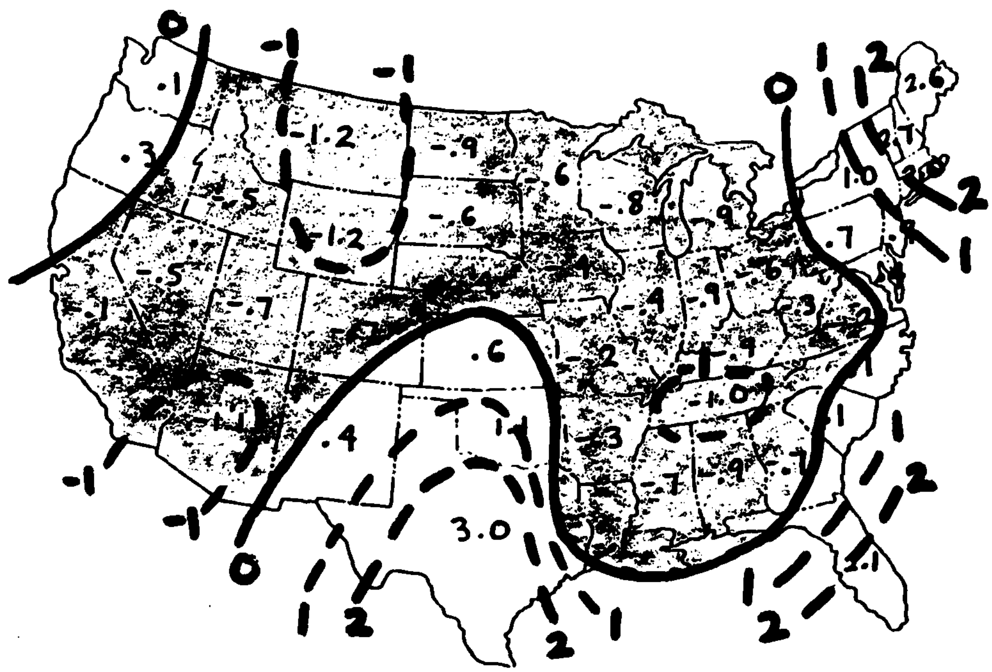

FIG. A1a. Precipitation distribution for January 1958. Anomaly for each state is given in units of standard deviations above or below the non-SSW mean. Below normal precipitation areas are shaded. Isopleth interval is one standard deviation.

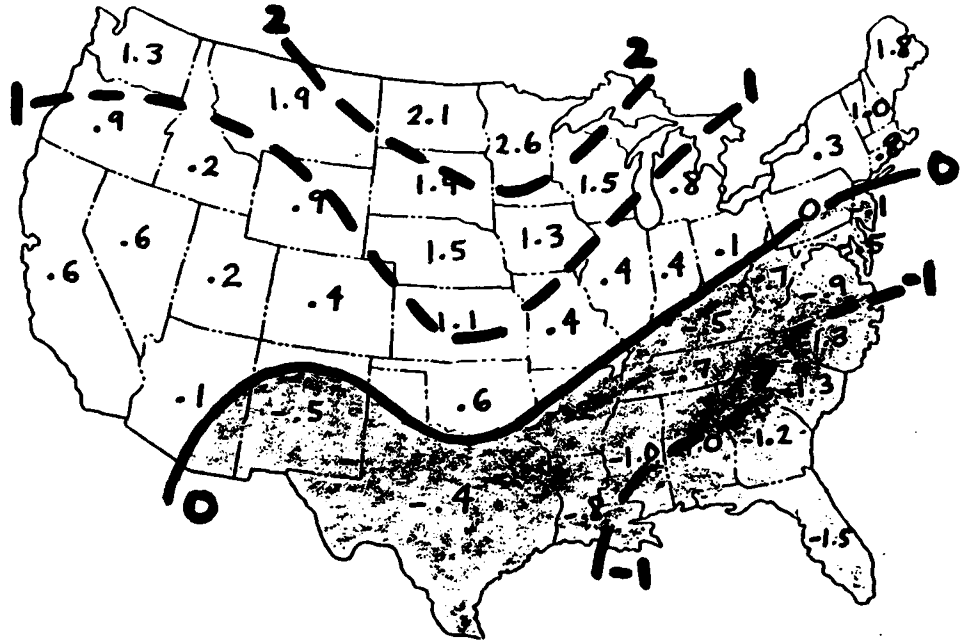

FIG. A2a. Surface temperature distribution for January 1958. Anomaly for each state is given in units of standard deviations above or below the non-SSW mean. Below normal temperature areas are shaded. Isopleth interval is one standard deviation.

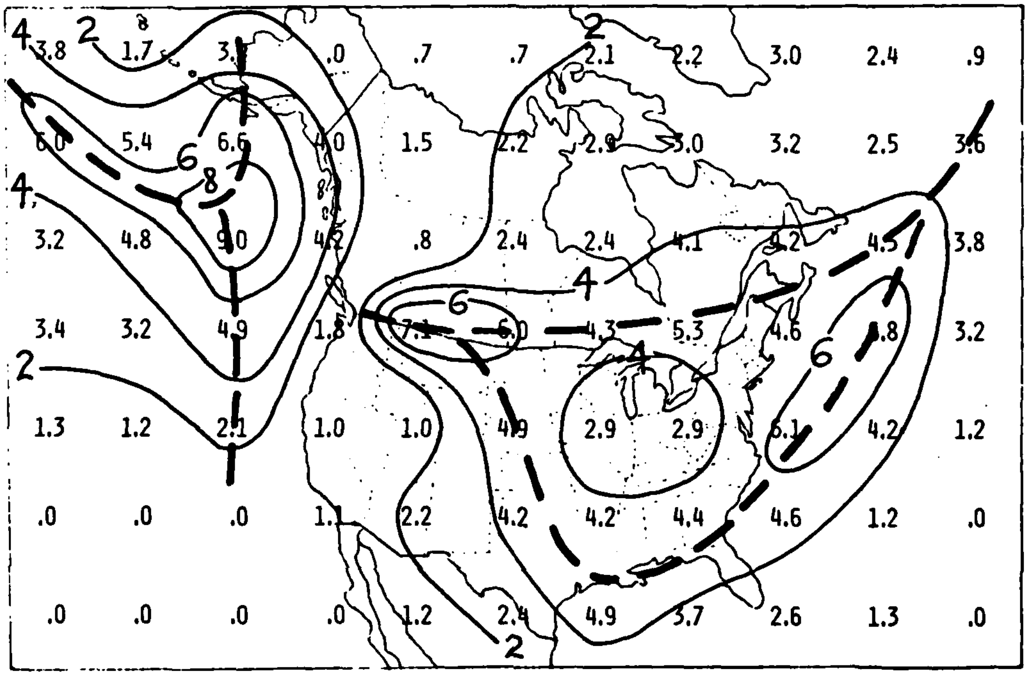

FIG. A3a. Cyclone distribution for January 1958. Numbers are the frequency of cyclones for each grid box. Axis of maximum cyclone frequency is indicated by dashed lines. Isopleth interval is every two cyclones.

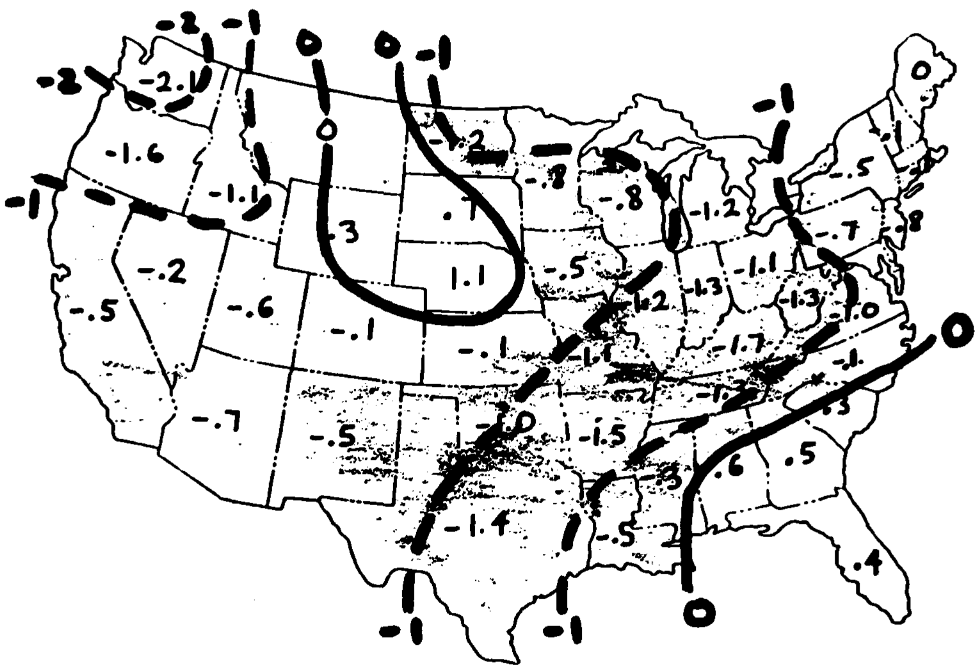

FIG. A1b. As Fig. A1a, except January 1963.

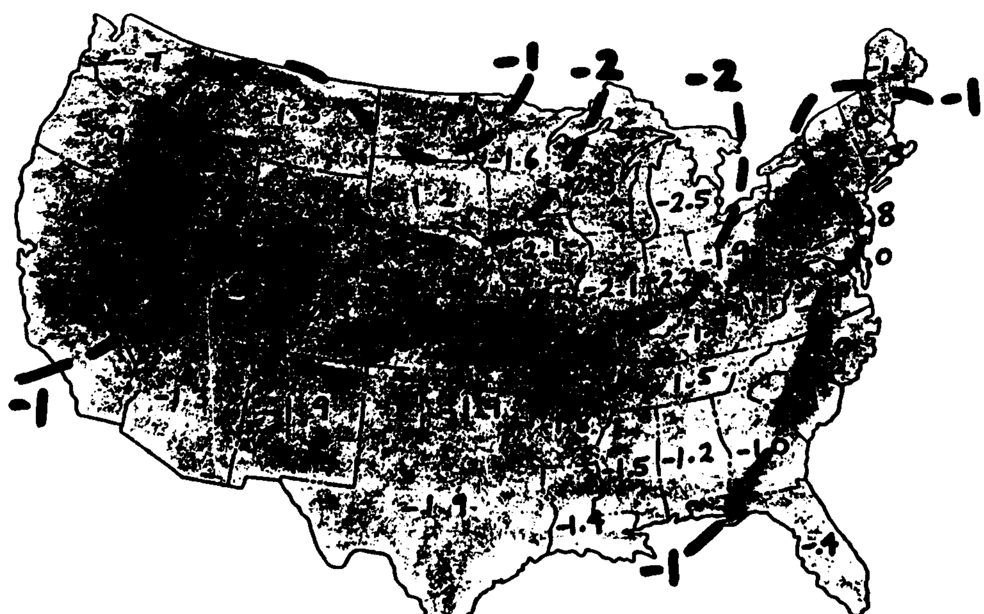

FIG. A2b. As Fig. A2a, except January 1963.

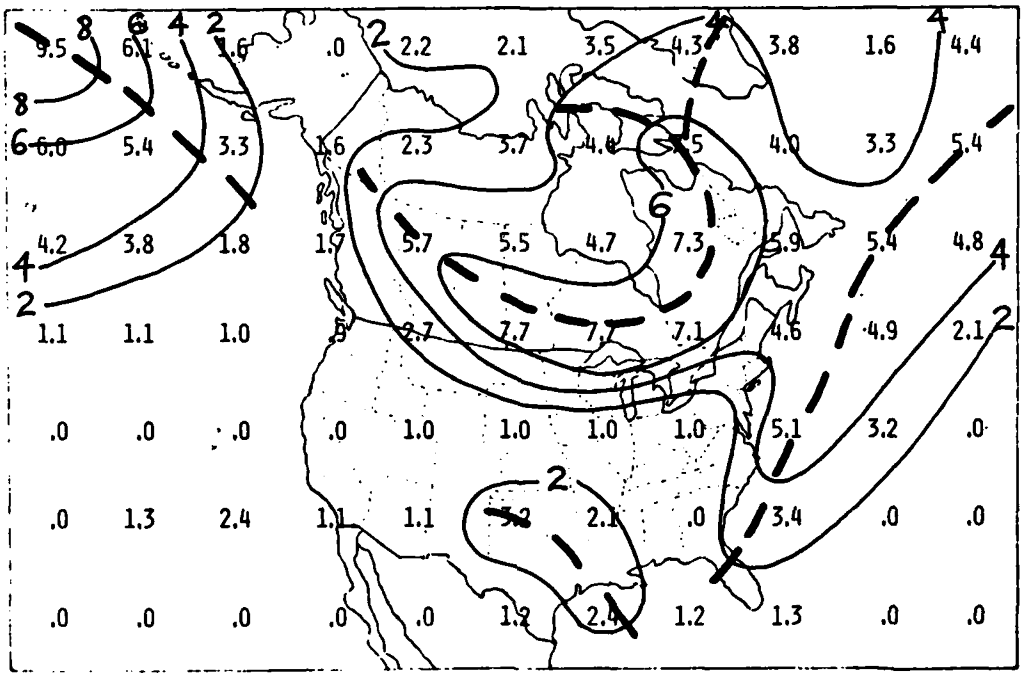

FIG. A3b. As Fig. A3a,except January 1963.

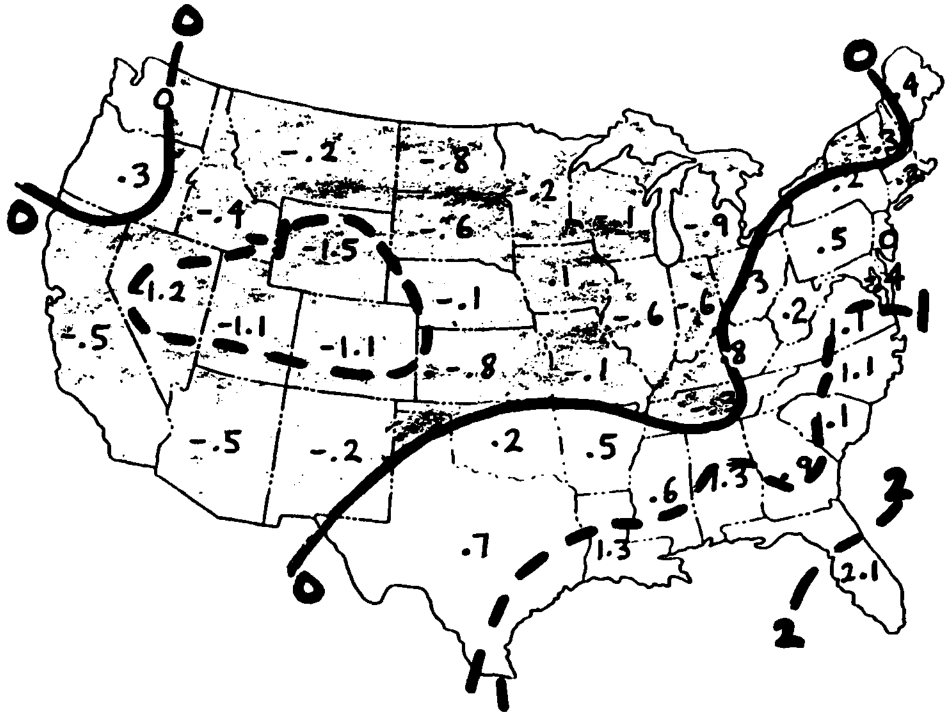

FIG. Alc. As Fig. Ala, except January 1966.

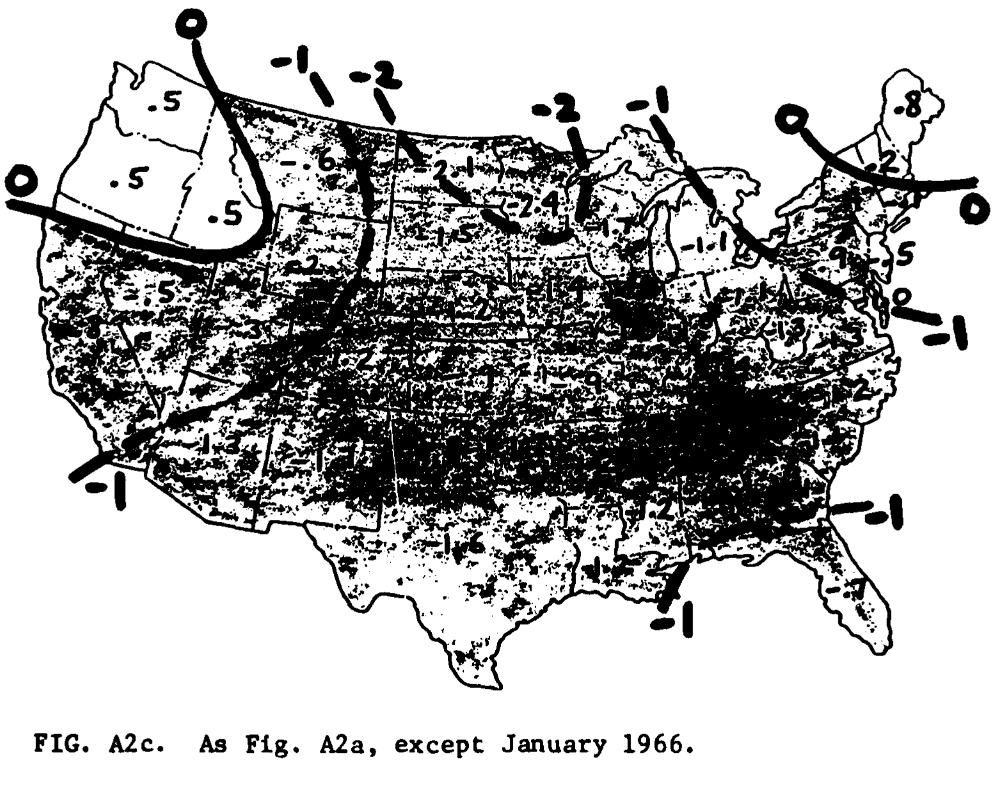

FIG. A2c. As Fig. A2a, except January 1966.

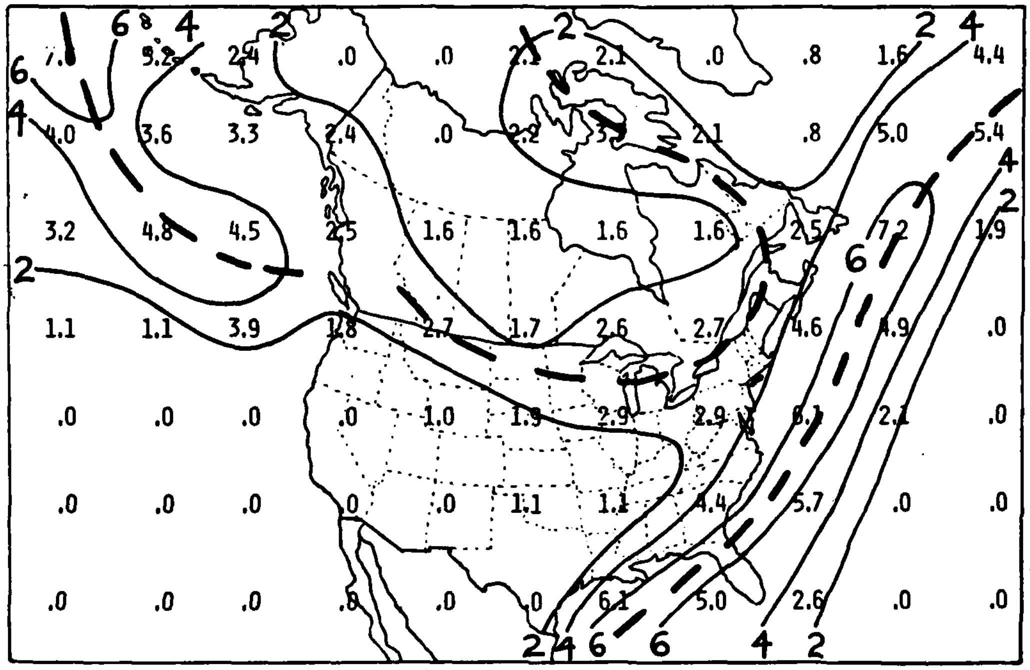

FIG. A3c. As Fig. A3a, except January 1966.

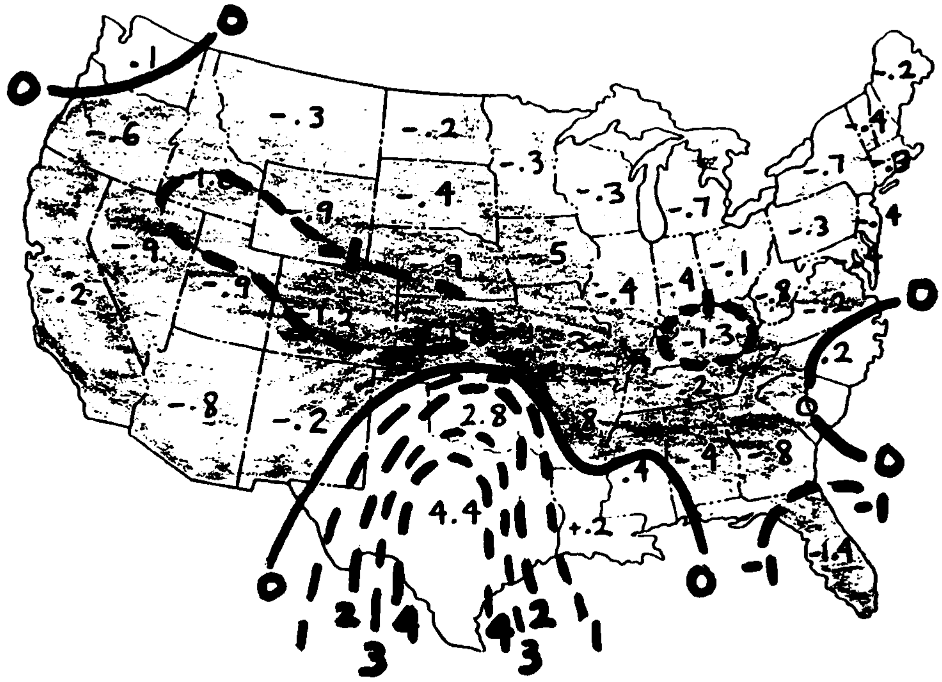

FIG. A1d. As Fig. A1a, except January 1968.

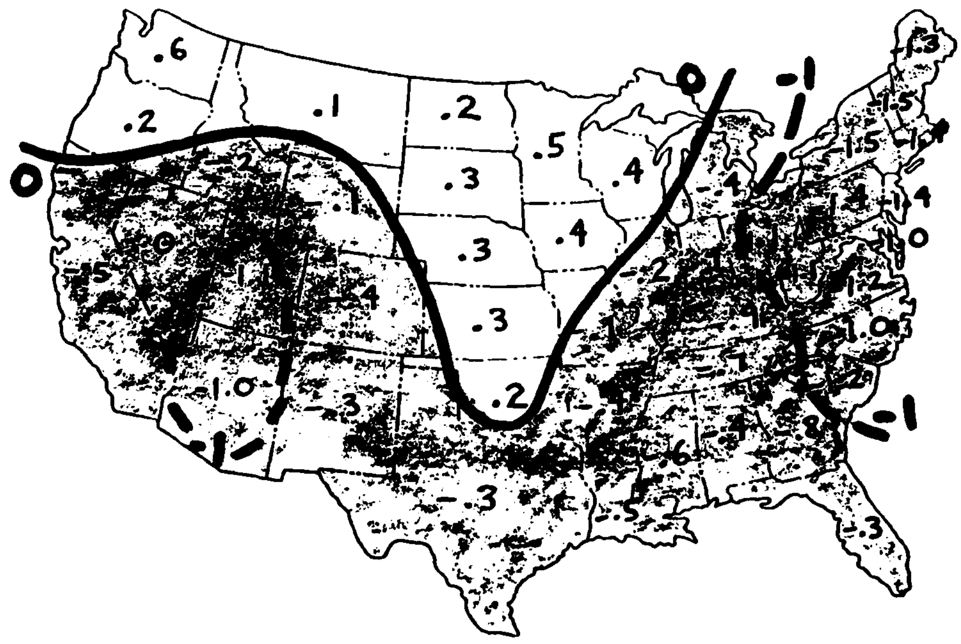

FIG. A2d. As Fig. A2a, except January 1968.

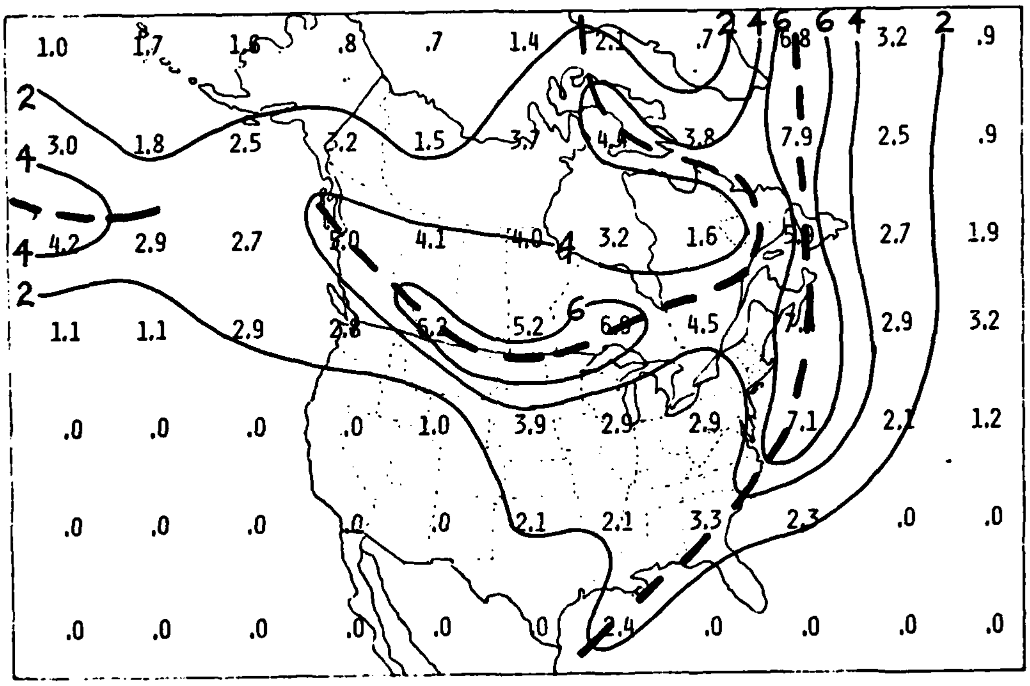

FIG. A3d. As Fig. A3a, except January 1968.

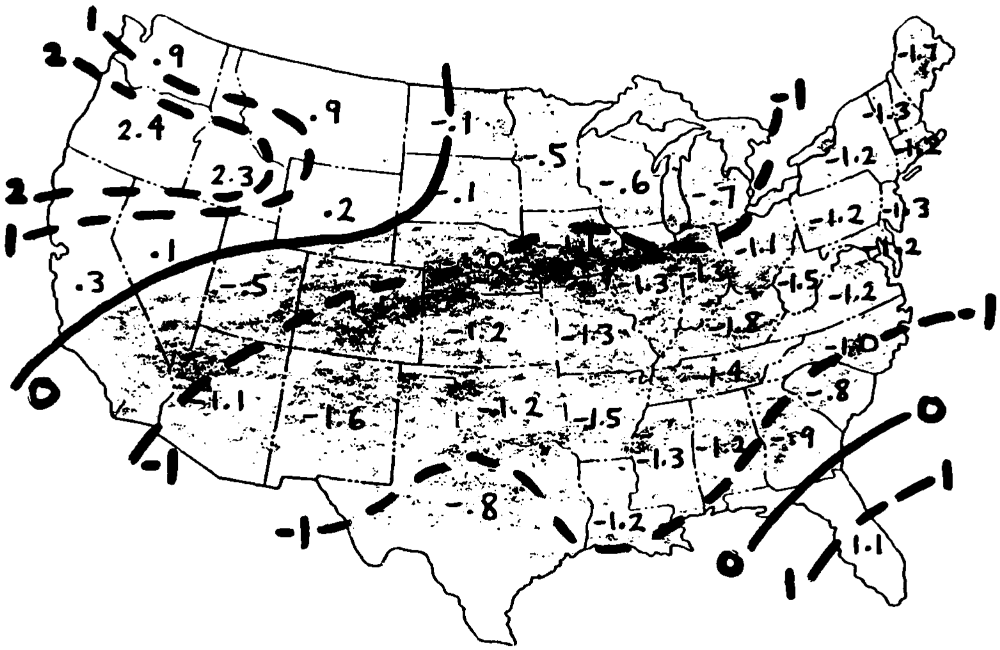

FIG. A1e. As Fig. A1a, except January 1970.

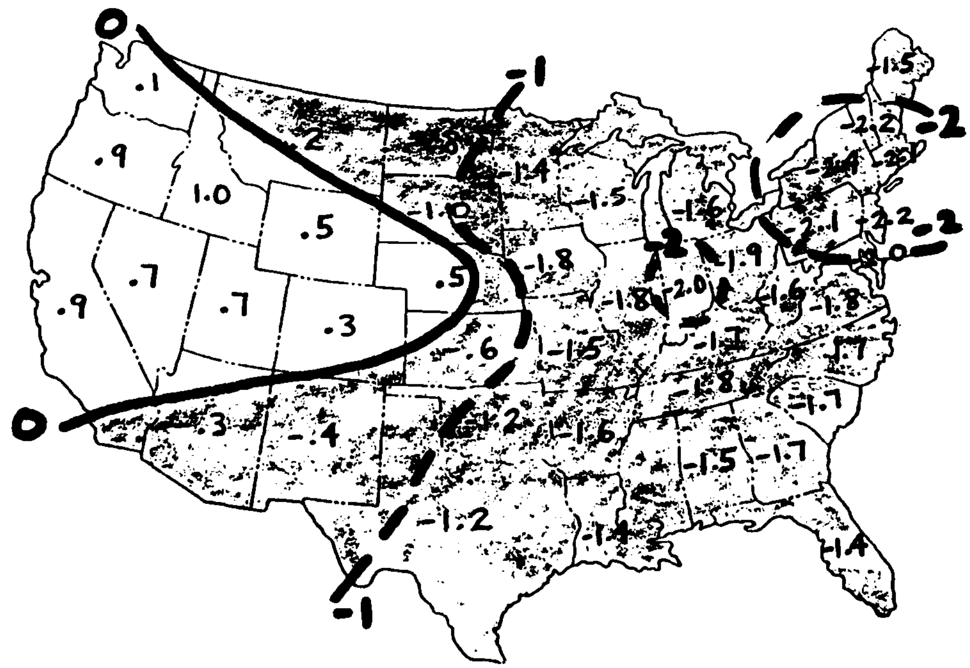

FIG. A2e. As Fig. A2a, except January 1970.

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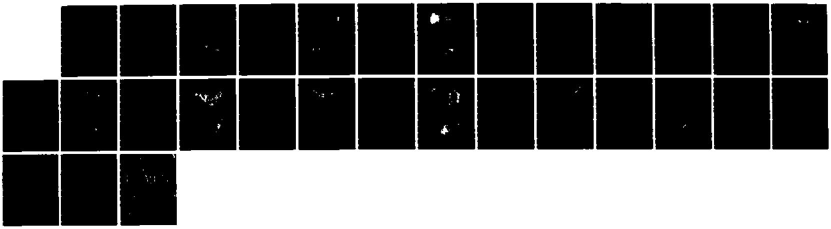

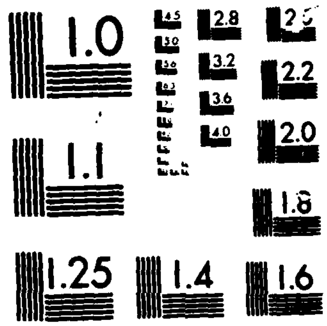

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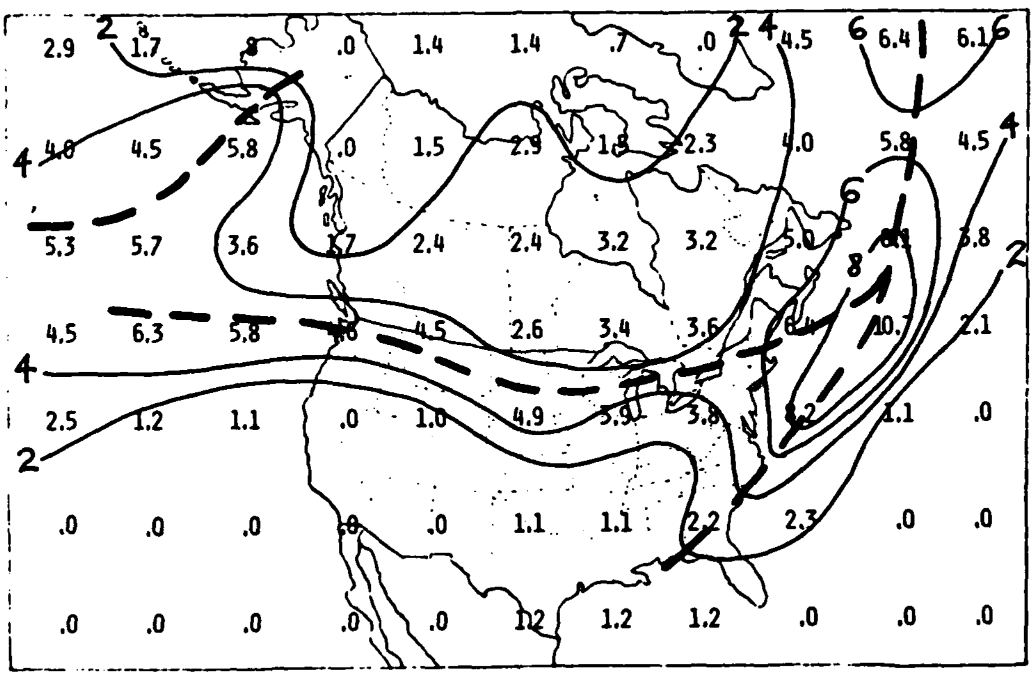

FIG. A3e. As Fig. A3a, except January 1970.

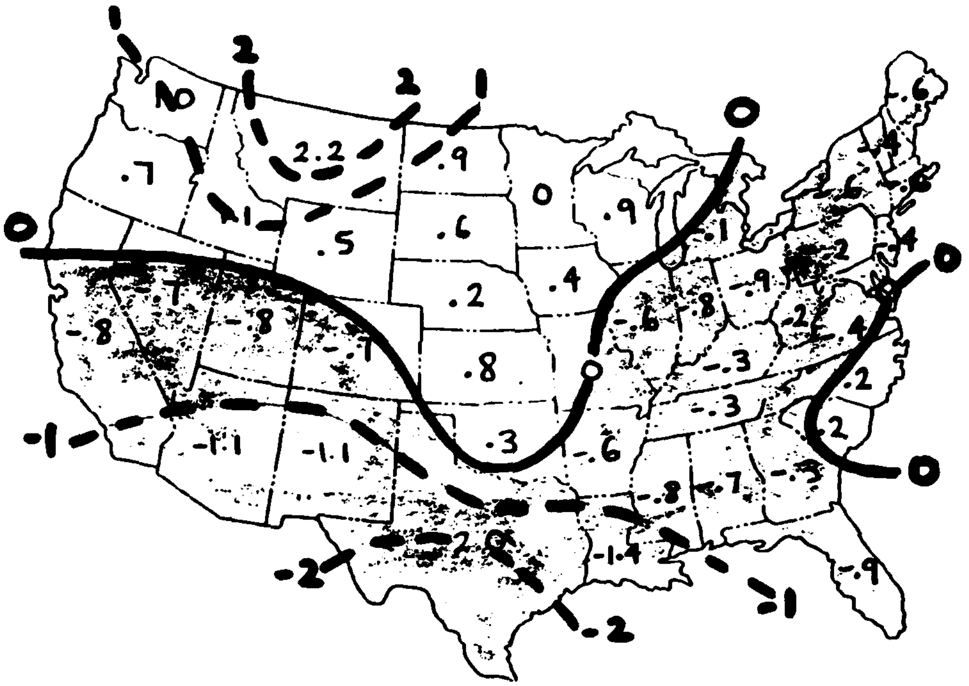

FIG. A1f. As Fig. A1a, except January 1971.

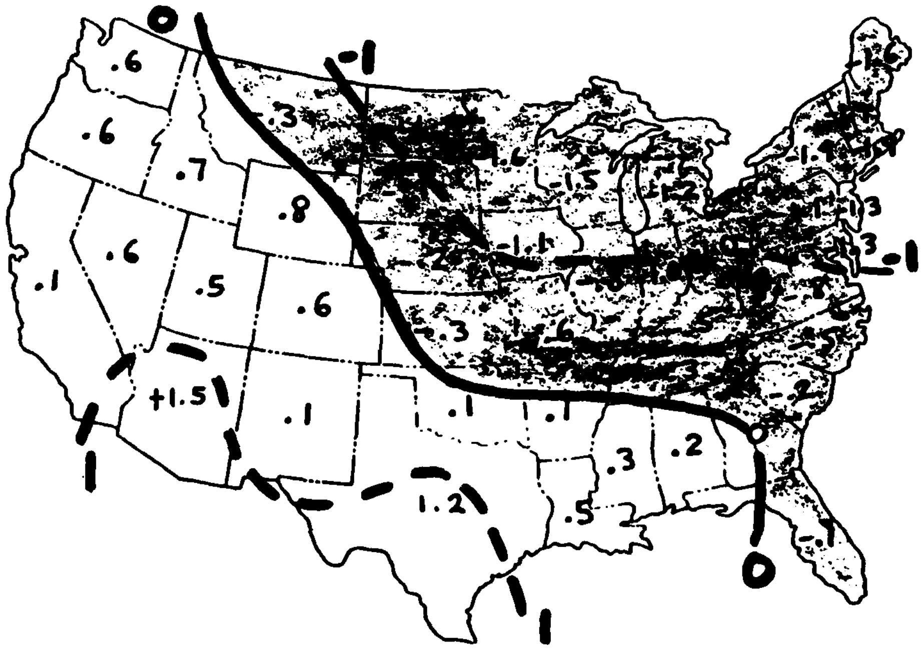

FIG. A2f. As Fig. A2a, except January 1971.

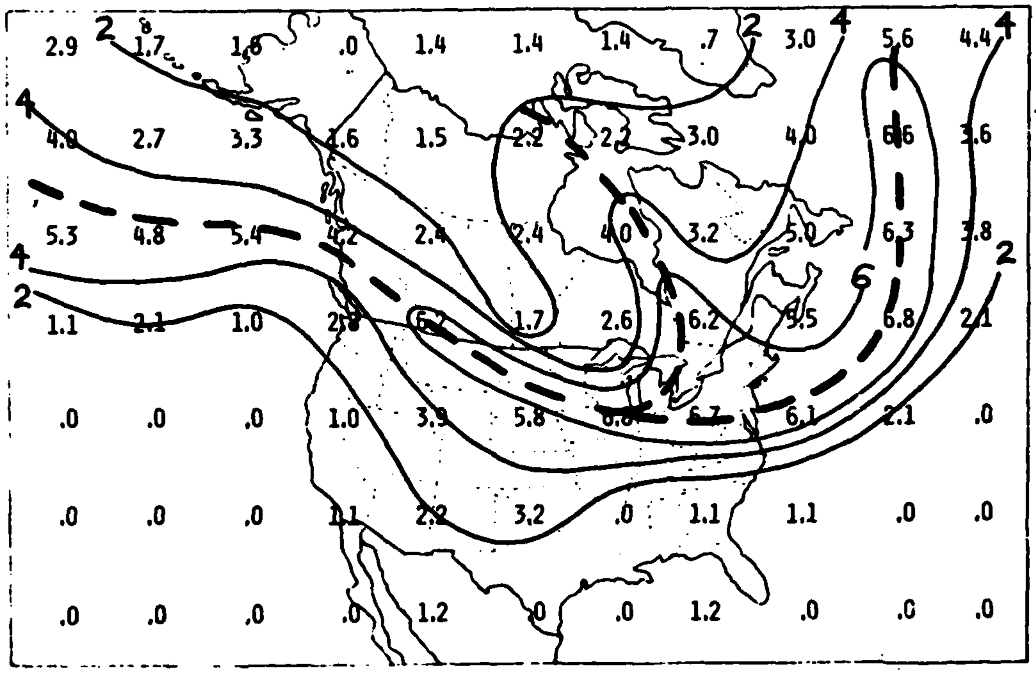

FIG. A3f. As Fig. A3a, except January 1971.

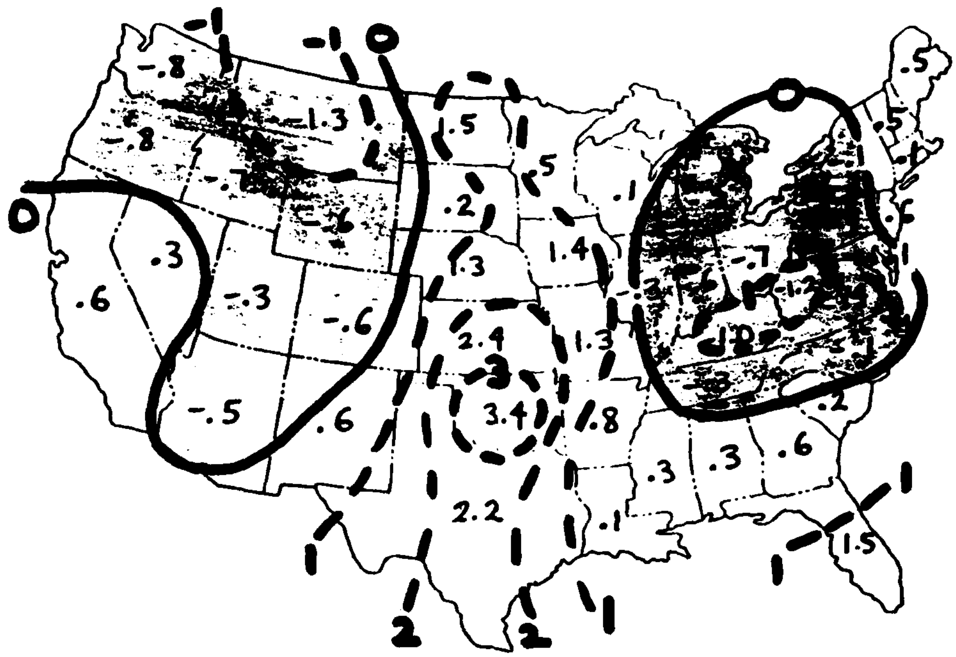

FIG. A1g. As Fig. A1a, except January 1973.

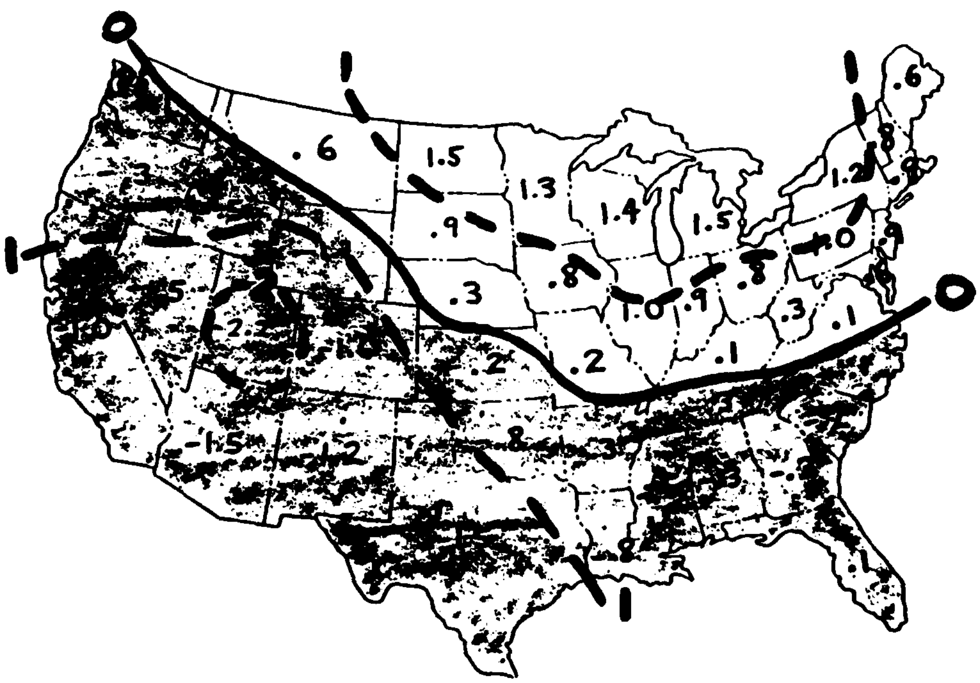

FIG. A2g. As Fig. A2a, except January 1973.

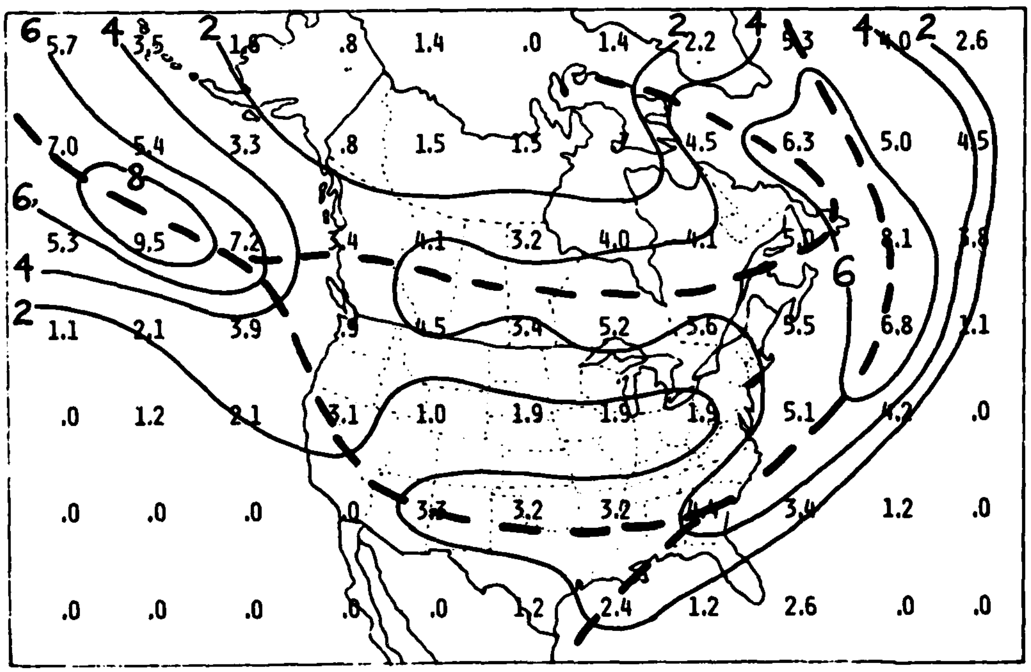

FIG. A3g. As Fig. A3a, except January 1973.

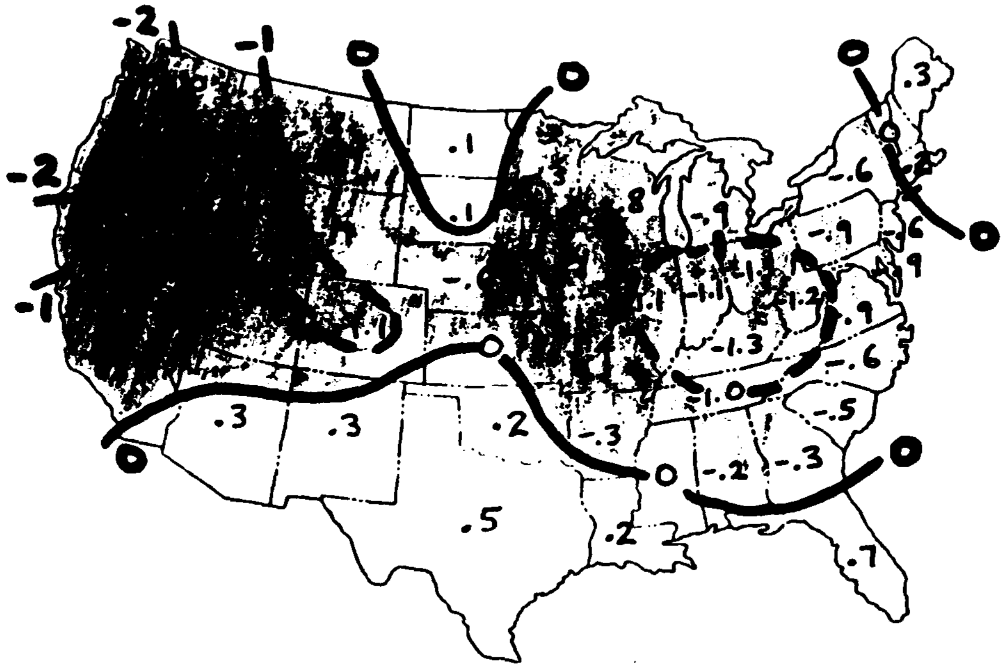

FIG. A1h. As Fig. A1a, except January 1977.

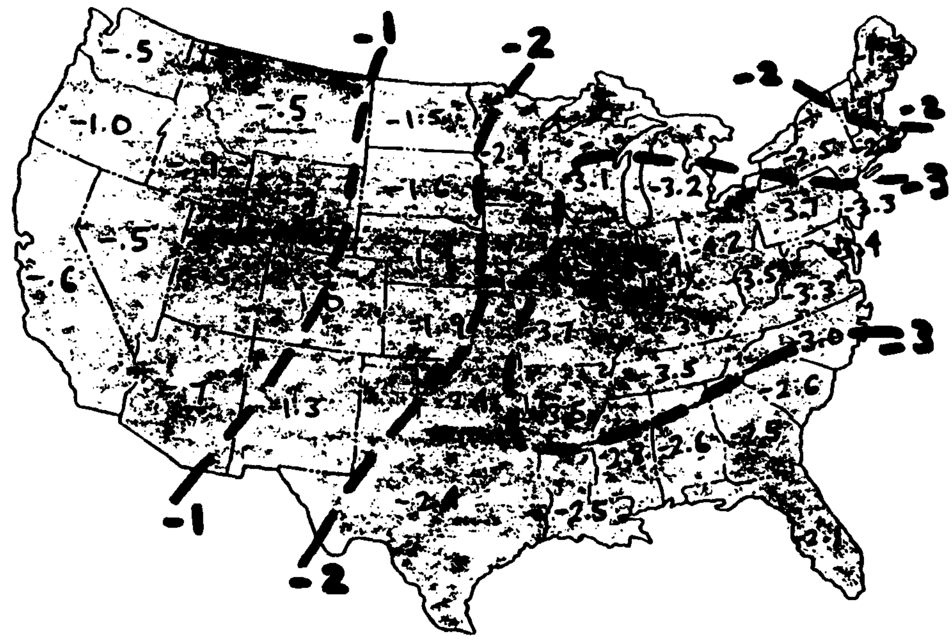

FIG. A2h. As Fig. A2a, except January 1977.

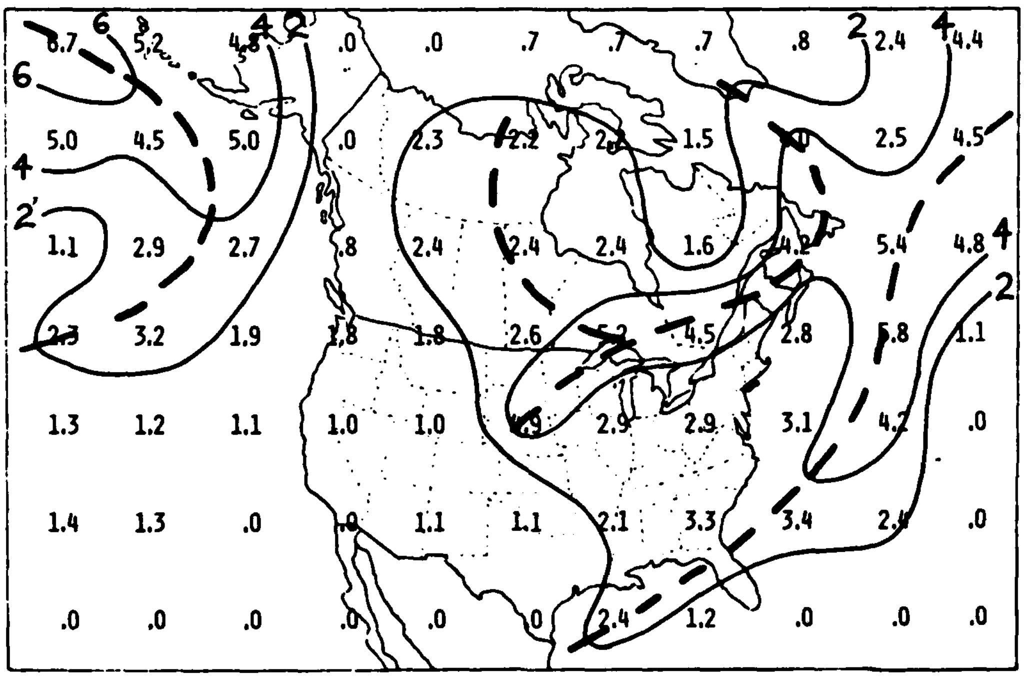

FIG. A3h. As Fig. A3a, except January 1977.

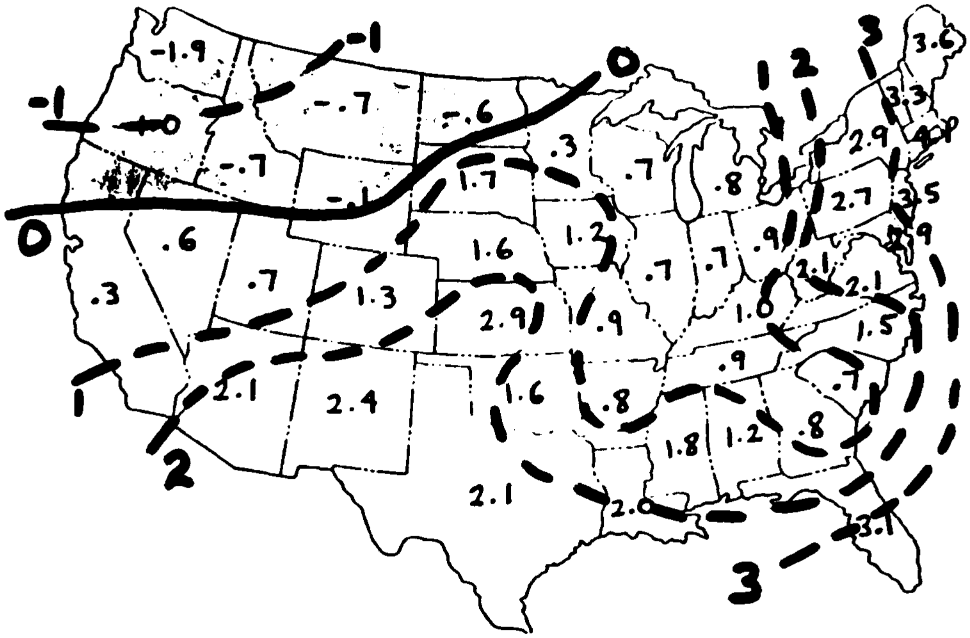

FIG. A1i. As Fig. A1a, except January 1979.

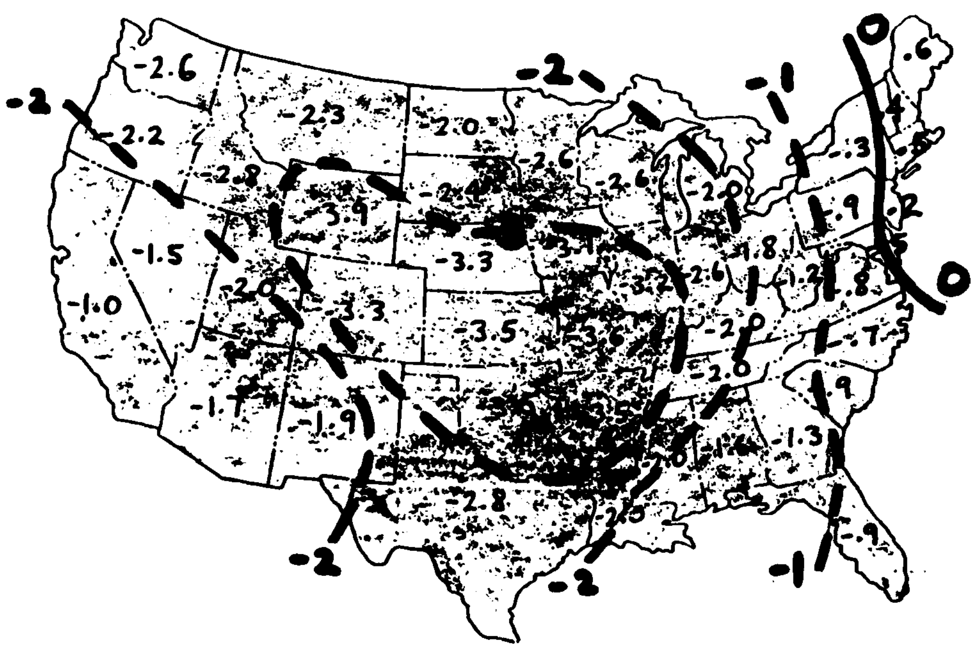

FIG. A2i. As Fig. A2a, except January 1979.

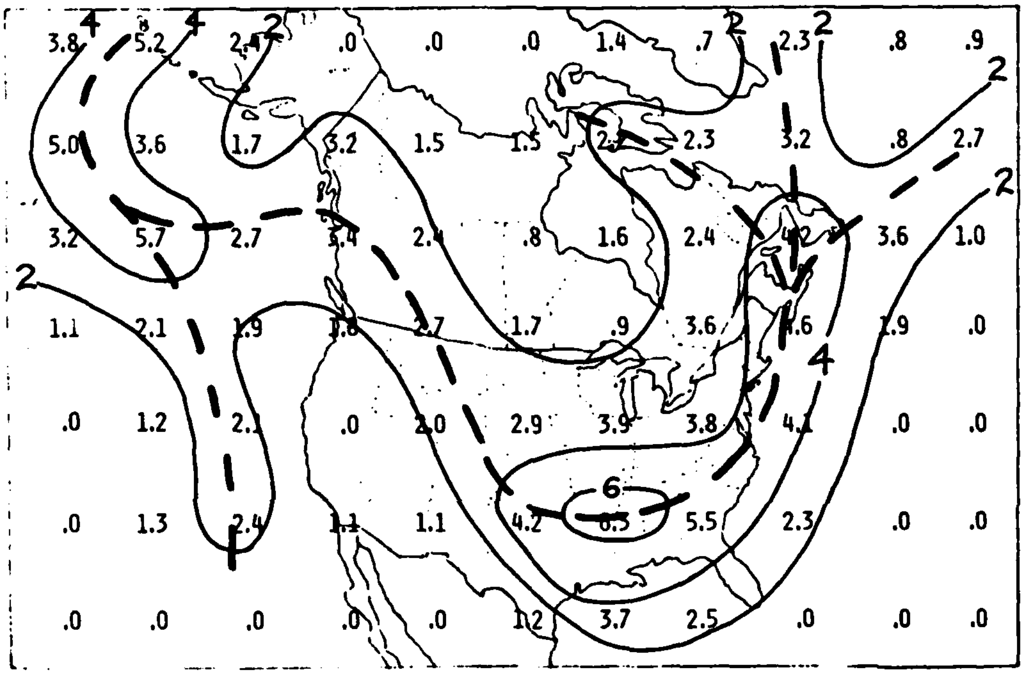

FIG. A3i. As Fig. A3a, except January 1979

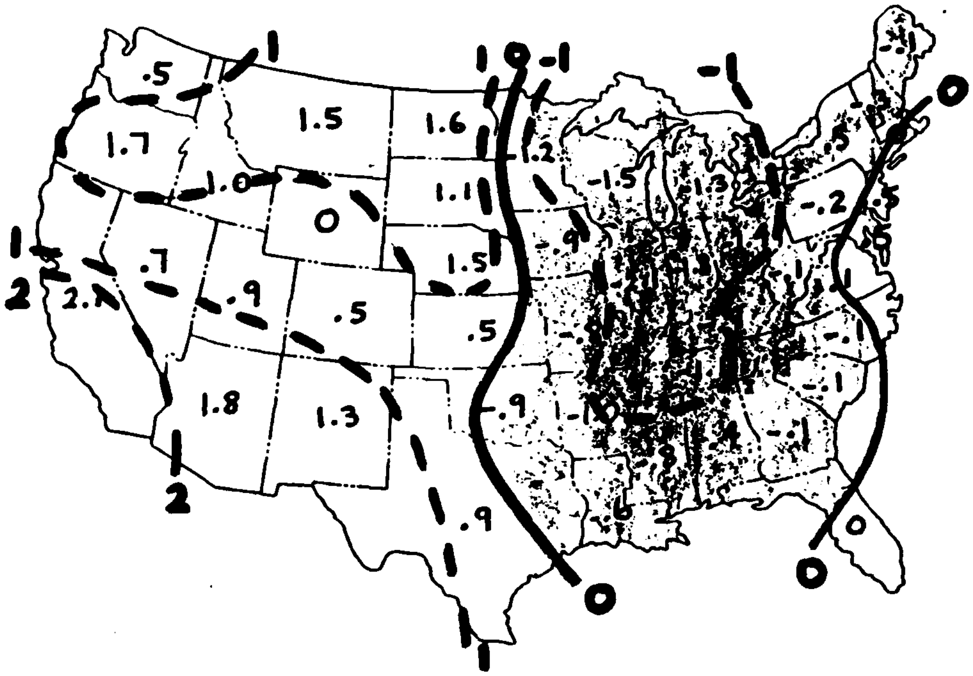

FIG. A1j. As Fig. A1a, except February 1958.

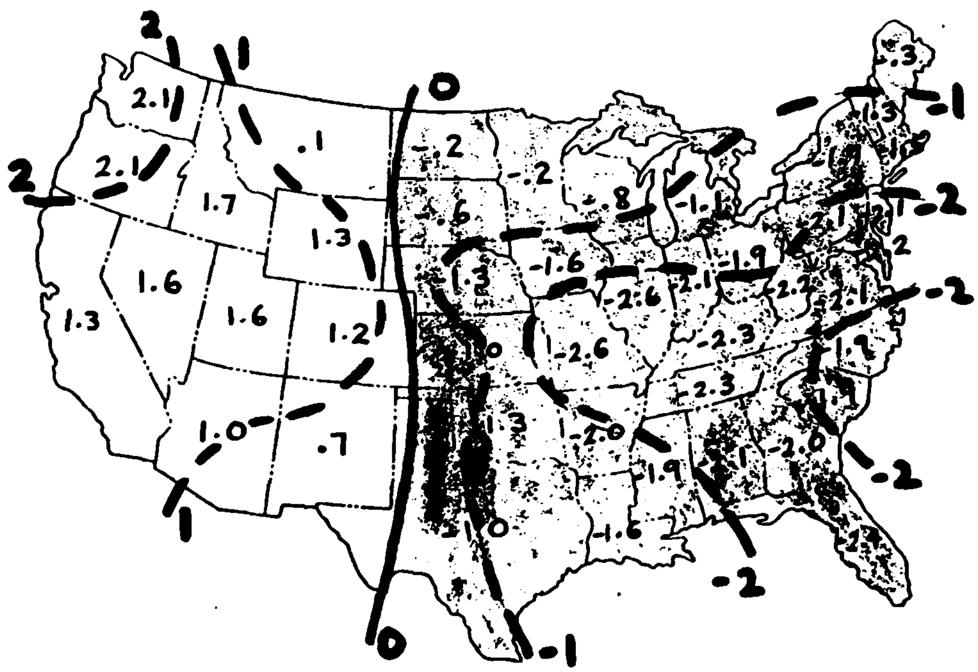

FIG. A2j. As Fig. A2a, except February 1958.

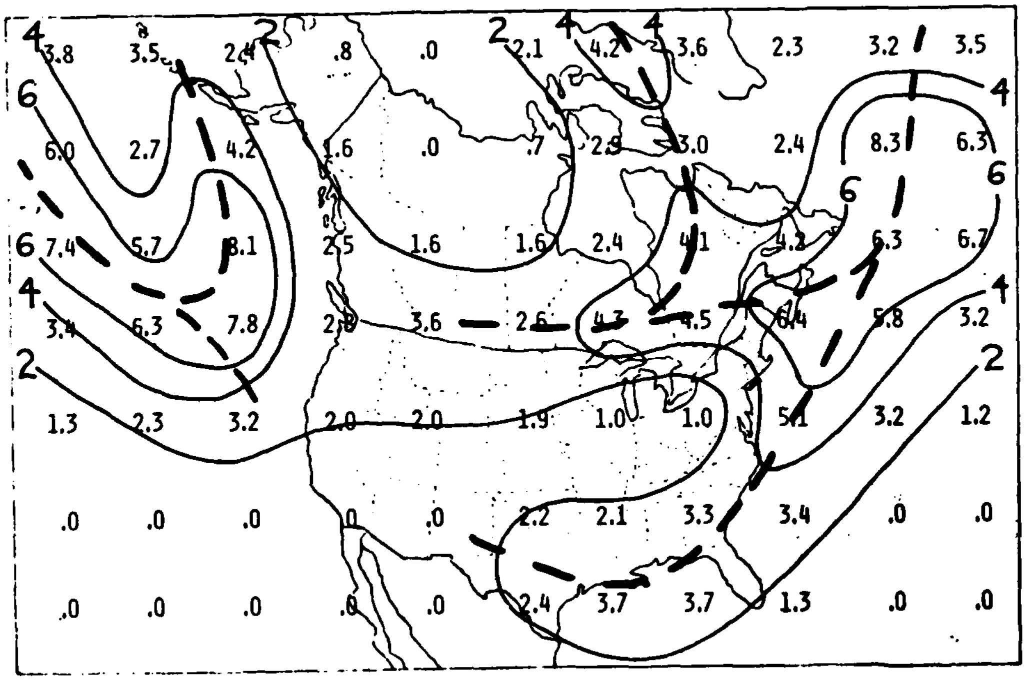

FIG. A3j. As Fig. A3a, except February 1958.

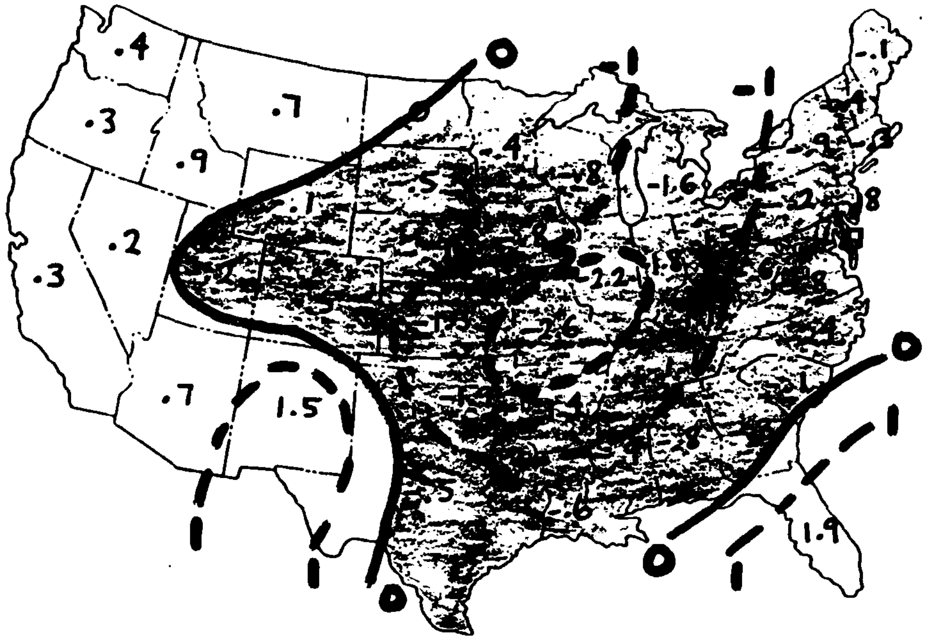

FIG. A1k. As Fig. A1a, except February 1963.

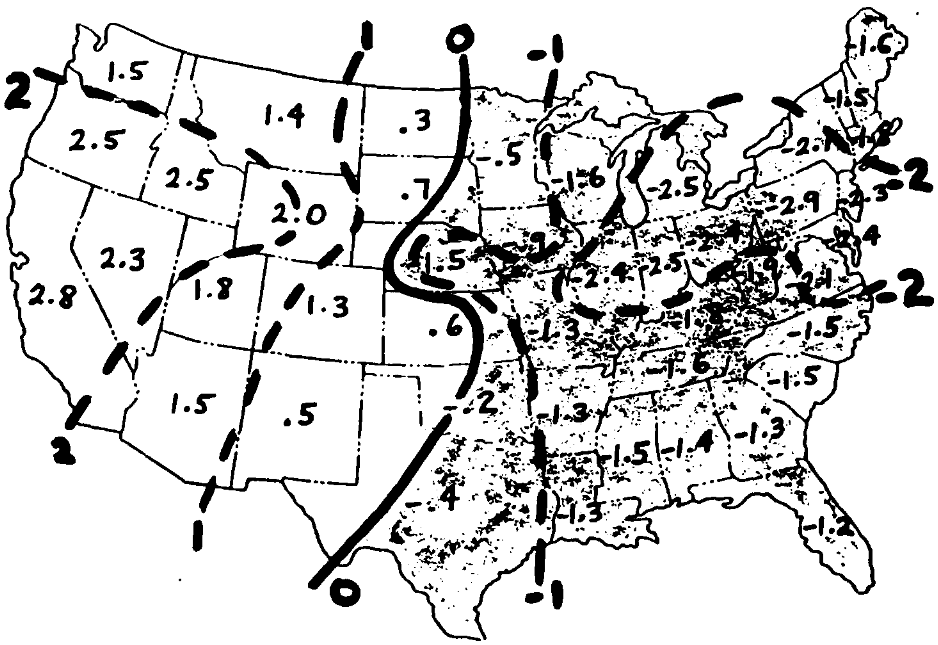

FIG. A2k. As Fig. A2a, except February 1963.

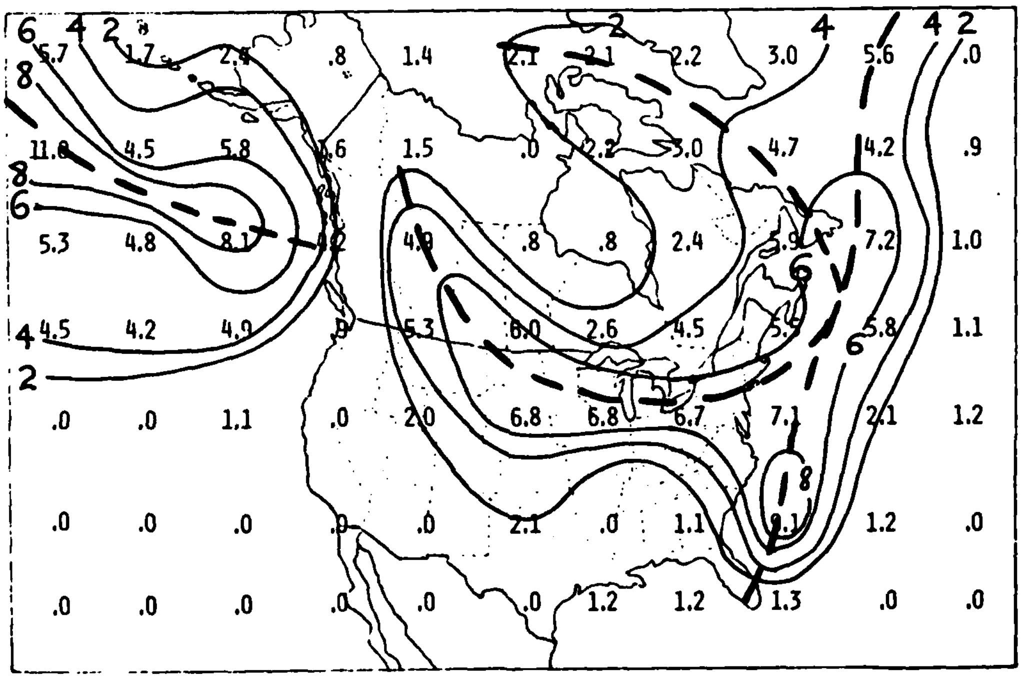

FIG. A3k. As Fig. A3a, except February 1963.

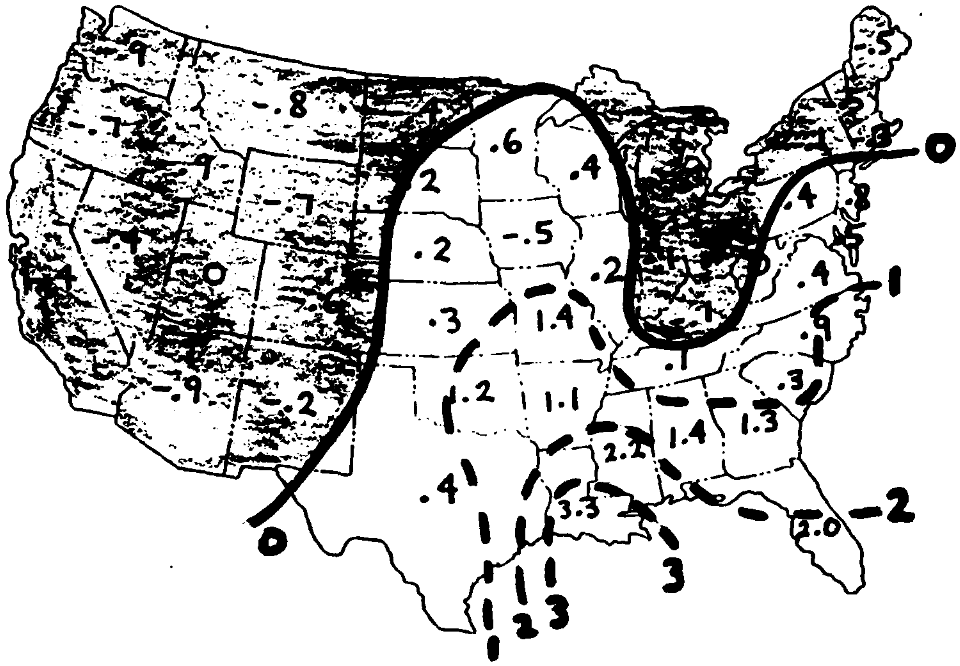

FIG. A1m. As Fig. A1a, except February 1966.

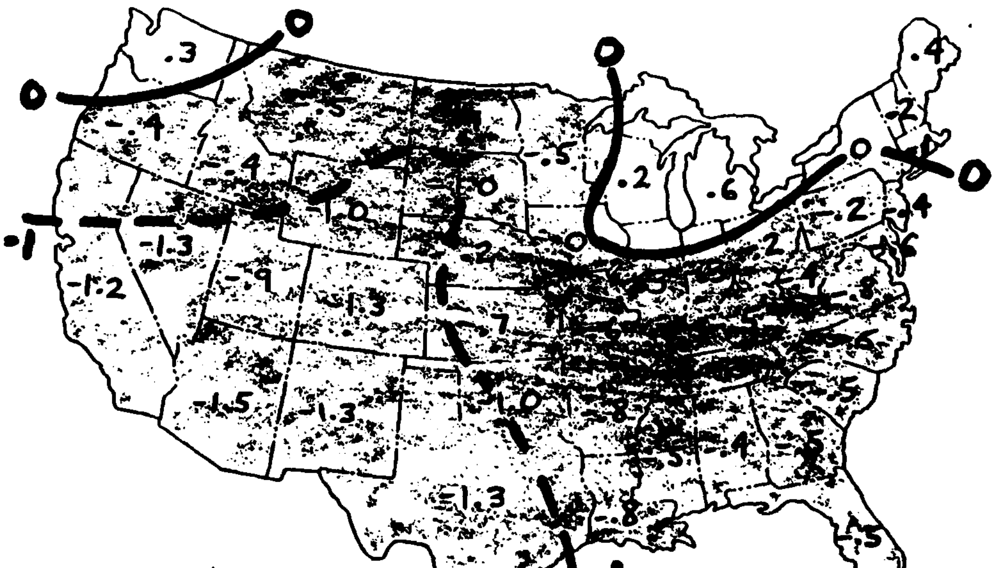

FIG. A2m. As Fig. A2a, except February 1966.

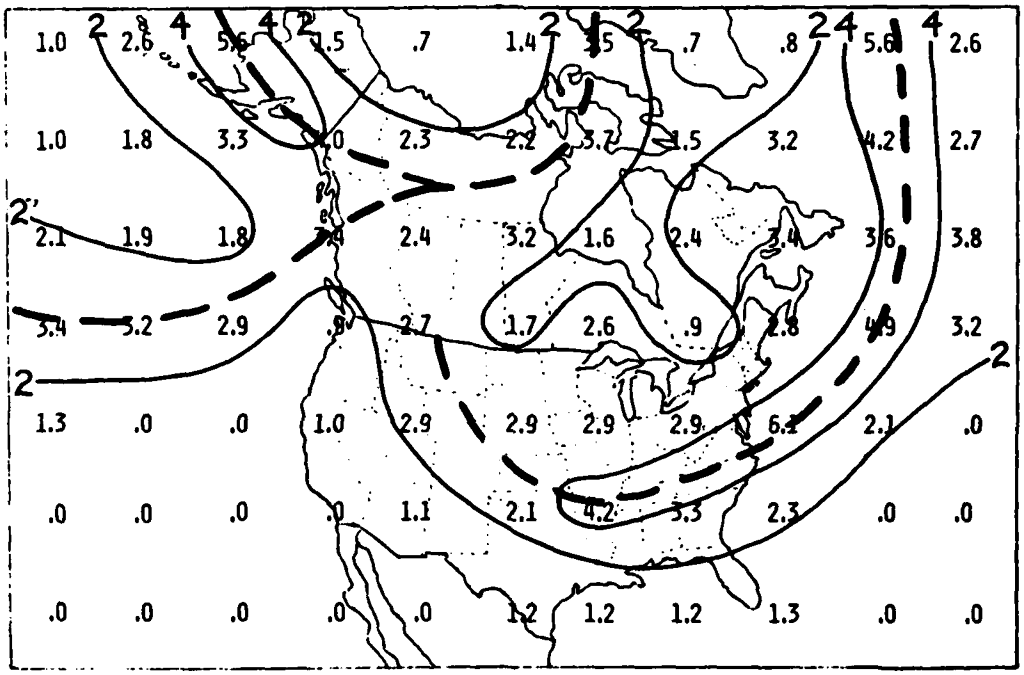

FIG. A3m. As Fig. A3a, except February 1966.

FIG. A1n. As Fig. A1a, except February 1970.

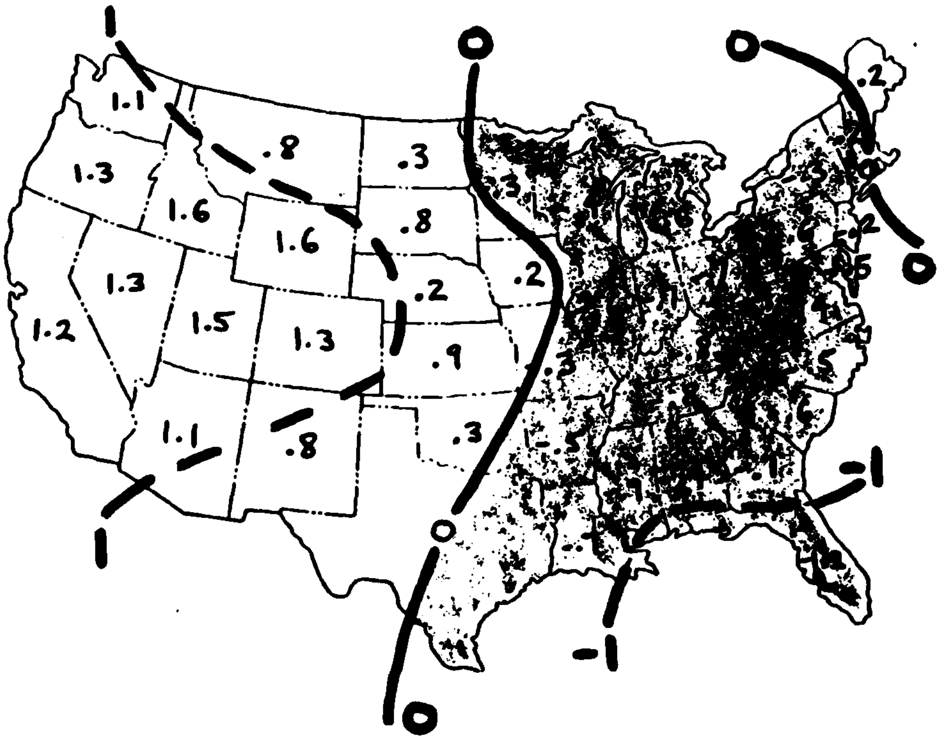

FIG. A2n. As Fig. A2a, except February 1970.

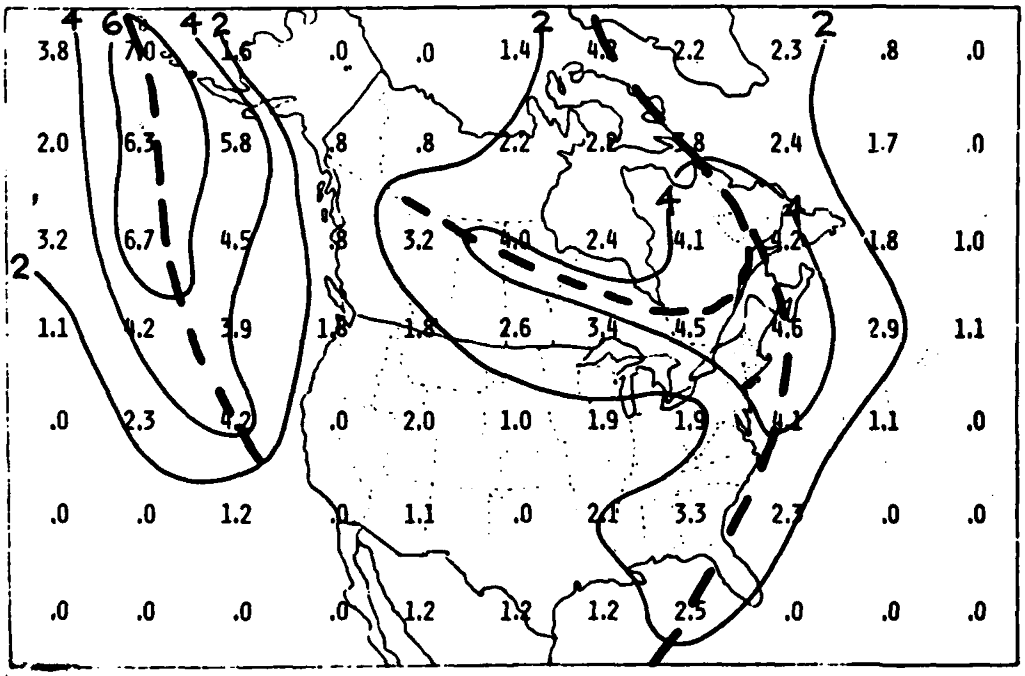

FIG. A3n. As Fig. A3a, except February 1970.

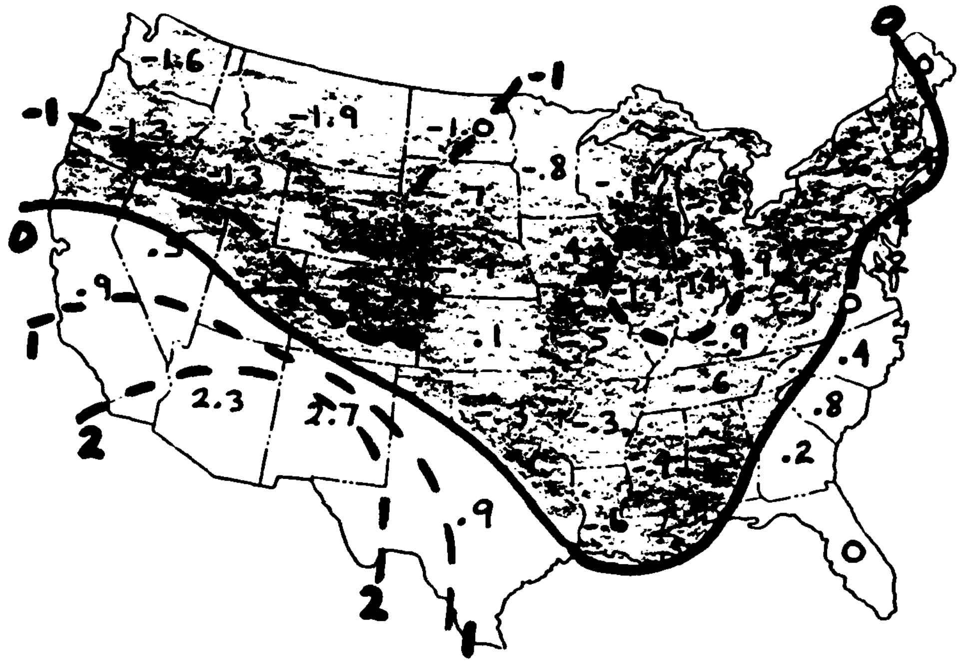

FIG. A1o. As Fig. A1a, except February 1973.

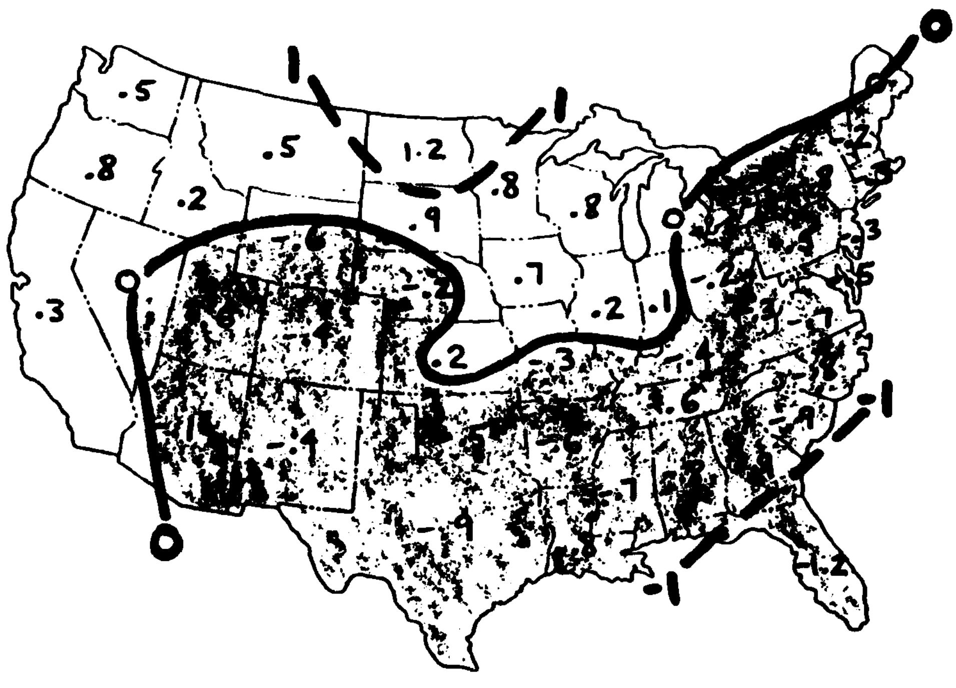

FIG. A2o. As Fig. A2a, except February 1973.

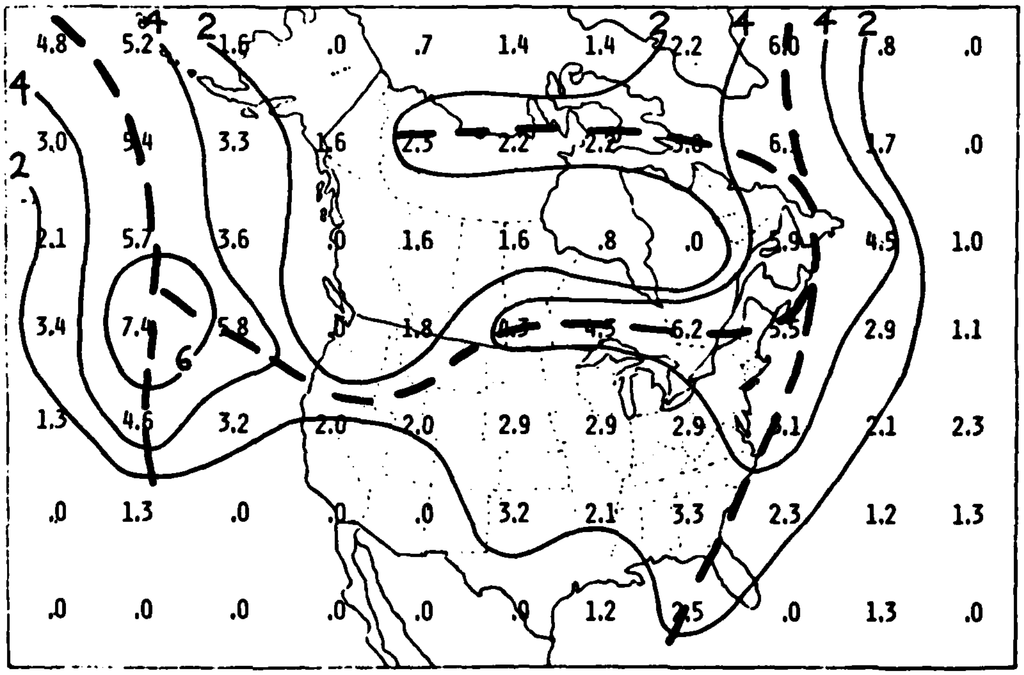

FIG. A3o. As Fig. A3a, except February 1973.

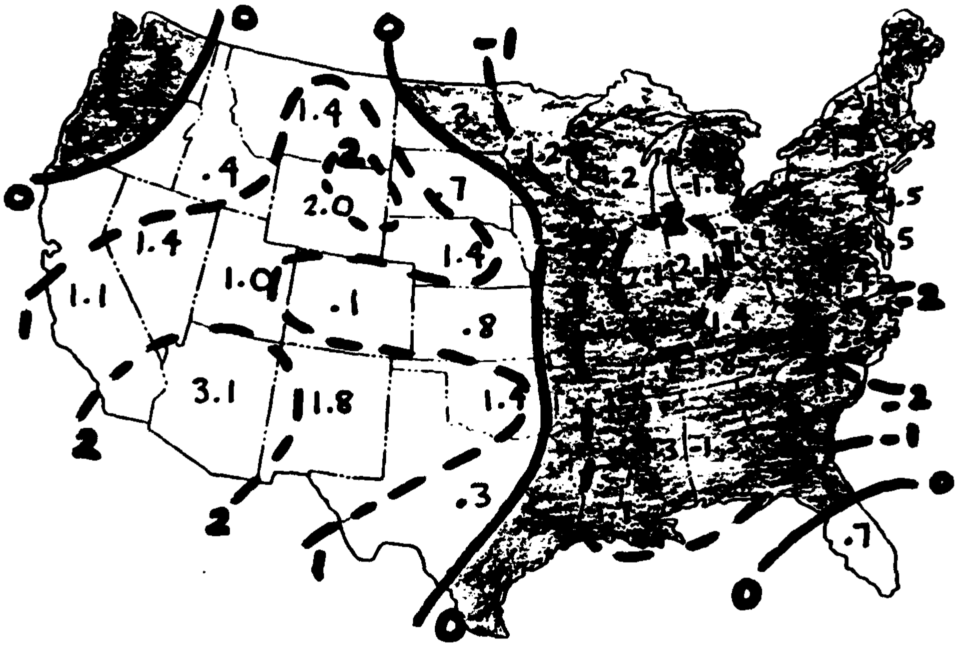

FIG. A1p. As Fig. A1a, except February 1978.

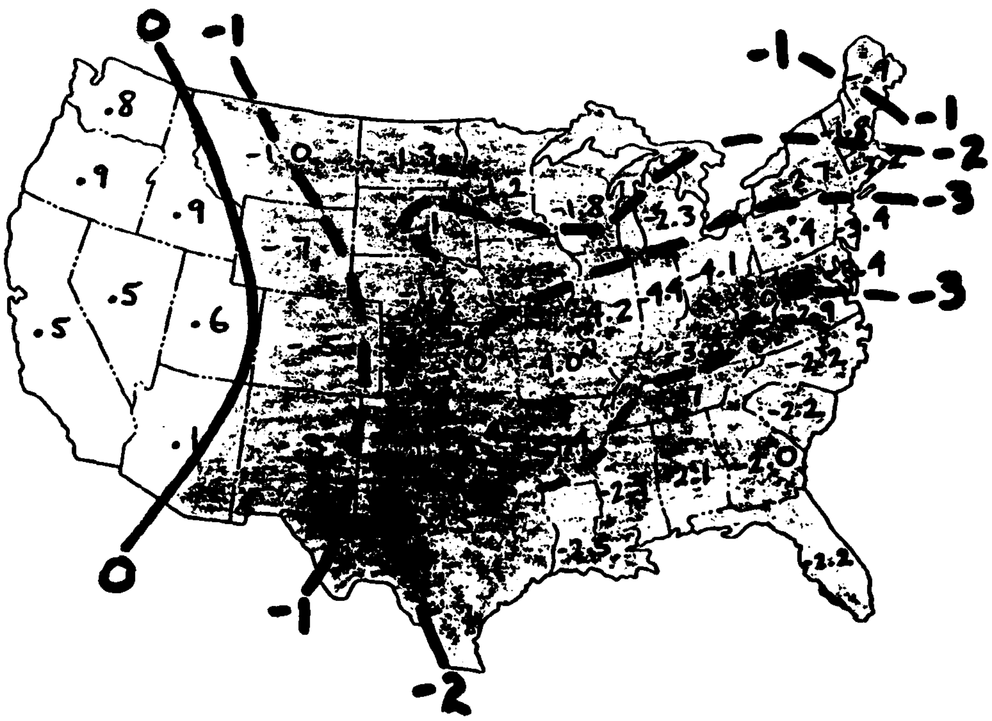

FIG. A2p. As Fig. A2a, except February 1978.

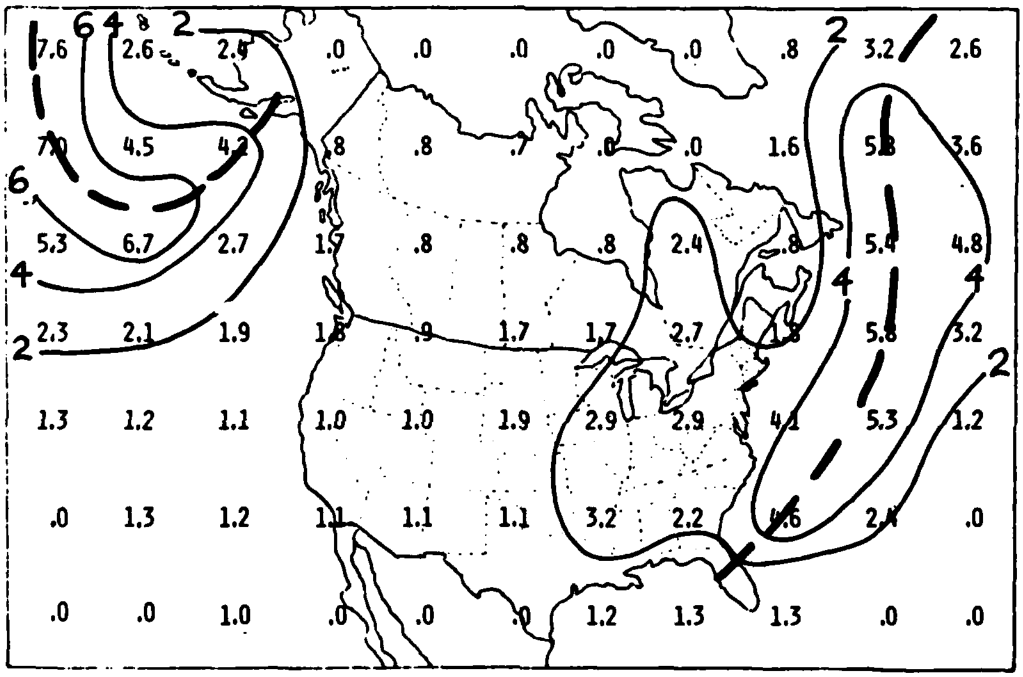

FIG. A3p. As Fig. A3a, except February 1978.

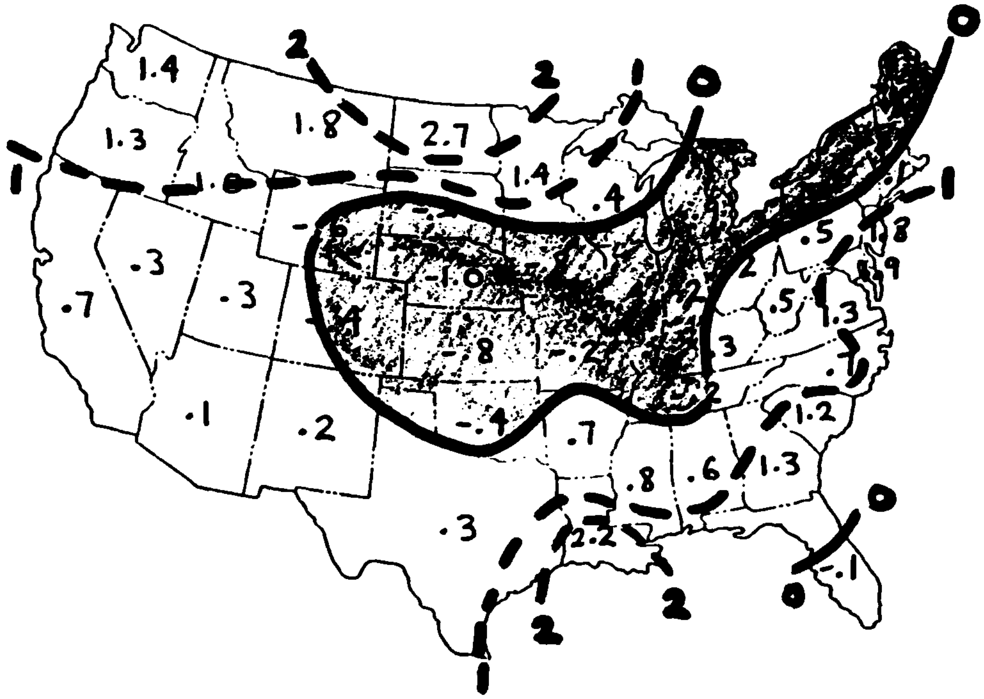

FIG. A1q. As Fig. A1a, except February 1979.

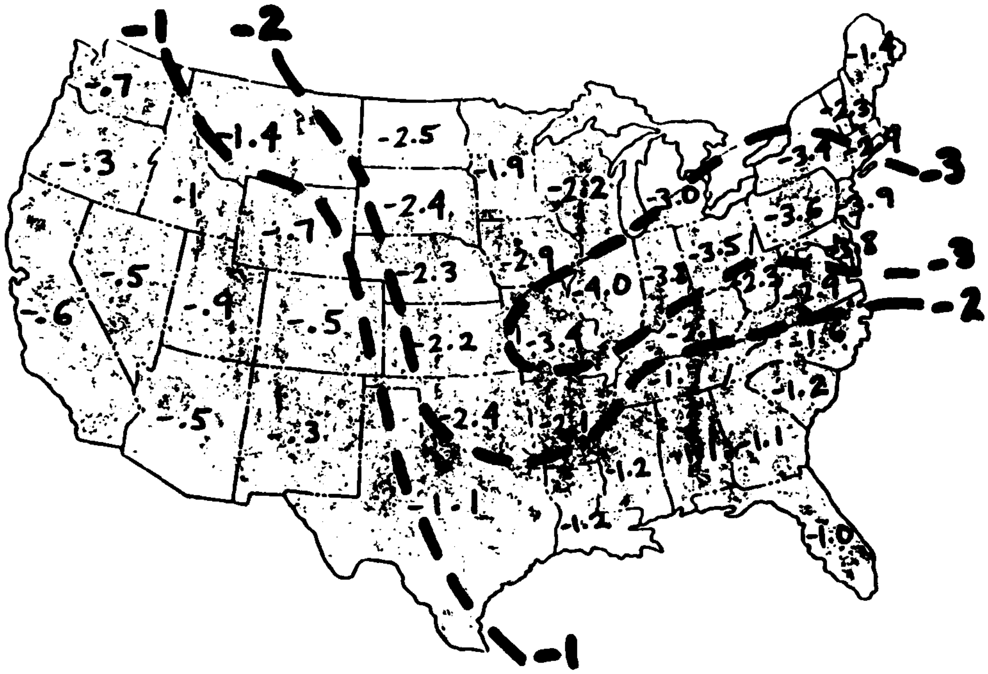

FIG. A2q. As Fig. A2a, except February 1979.

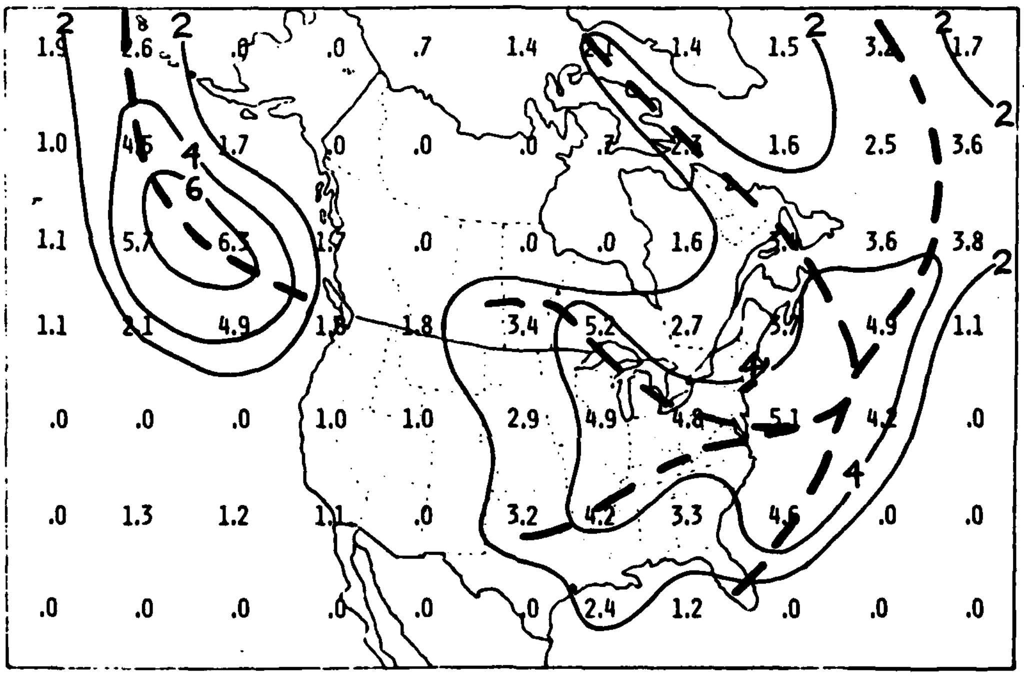

FIG. A3q. As Fig. A3a, except February 1979.

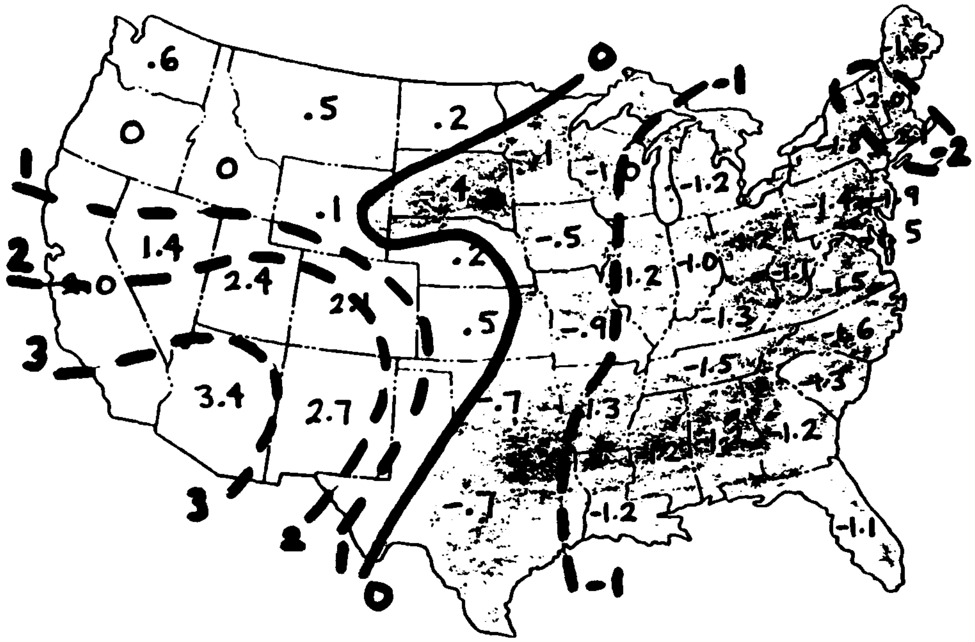

FIG. A1r. As Fig. A1a, except February 1980.

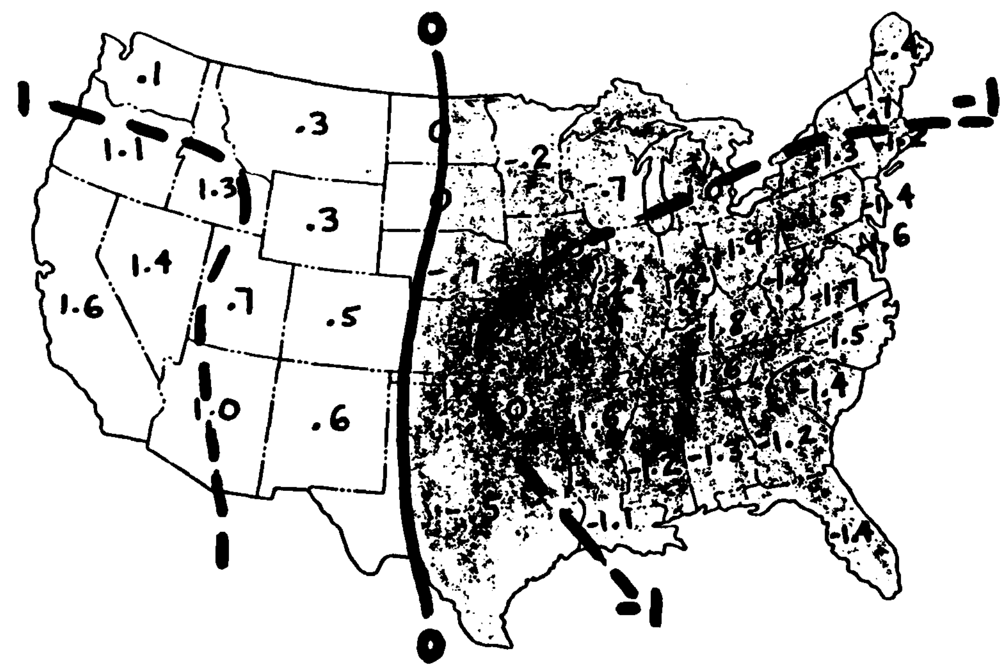

FIG. A2r. As Fig. A2a, except February 1980.

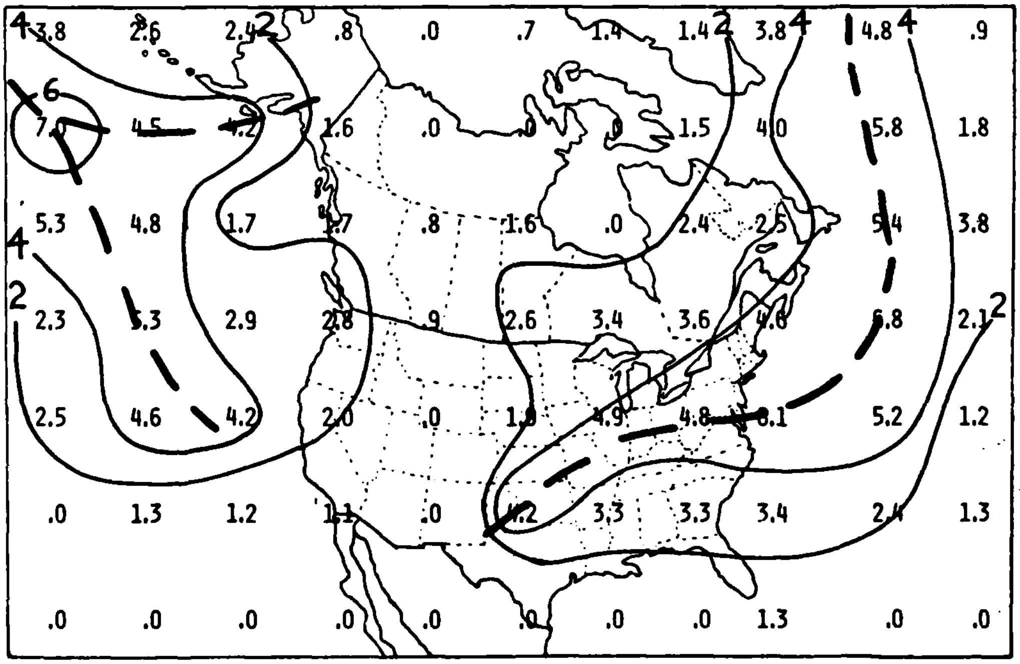

FIG. A3r. As Fig. A3a, except February 1980.

VITA

Donald Albert Douglas graduated from St. Petersburg Junior College in 1964 and entered the Air Force in 1965. He served for seven years in Air Weather Service with duties as a weather observer at South Ruislip England, and as a weather forecaster at Malmstrom AFB, Montana. After attending the University of Utah from 1972 to 1974, he graduated with a Bachelor of Science degree in meteorology and was subsequently commissioned in the Air Force. He then served seven years as a weather officer at Charleston AFB, South Carolina and RAF Mildenhall, England. He began graduate studies at Texas A&M University in August, 1981, sponsored by the Air Force Institute of Technology. The author is currently at Kirtland AFB, New Mexico, with duty as a staff meteorologist for the Air Force Weapons Laboratory. His permanent mailing address is: 1391 64 Avenue North, St. Petersburg, Florida 33702.

ITINERARY

Program Visit by Maj Knutson and Maj Bjerkaas

30 Nov 85 - 2229L Maj Knutson arrives in Albuquerque on American Airlines Flight 349.

1 Dec 85 - 2229L Maj Bjerkaas arrives on American Airlines Flight 349.

Reservations have been made at East VOQ, confirmed by Antonette Gamble, 344-3494.

1 Dec 85 - Social (Lynn), Christorian House, 1800 hours.

2 Dec 85 - 0800L Meet and greet 2WS visitors.

0815L OL-B overview and concerns.

0930L Safety and project review with Maj Luces.

1100L View from 2WS.

1130L Lunch at K&I Diner.

1300L Project review with Capts Douglas and Franchi.

Maj Bjerkaas departs for EOSAEL Conference in Las Cruces with Maj Luces.

3 Dec 85 - 0830L Projects with Capt Davidson.

1000L Security review and optical turbulence tutorial with Mr Furukawa.

1200L Lunch at West O-Club.

1300L Details of CLEAR program (Mr Furukawa & Lt Col Bliss).
- history
- current efforts
  - -- simulation
  - -- 3Dneph analysis
- PHOENEX
- FY86 and beyond

1500L Other topics or checklist reviews.

4 Dec 85 - Maj Knutson departs for OL-A, Holloman AFB NM using rental car.

6 Dec 85 - 1300L Maj Knutson departs from Holloman AFB NM arriving Albuquerque late in the afternoon.

Maj Bjerkaas arrives in Albuquerque sometime late in the afternoon. Both have rooms at VOQ for this night.

7 Dec 85 - 0935L Both depart Albuquerque on American Airlines Flight 390.

END
FILMED
4-86
DTIC